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GROUND-BASED SIMULATION TECHNIQUES

By

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October 1967

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

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NORTH AMERICAN AVIATION, INC.
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This report has been reviewed by the U. S. Army Aviation Materiel
Laboratories and the U. S. Army Human Engineering Laboratories and
is considered to be technically sound. The work was performed
under Contract DA 44-177-AMC-406(T).

Various kinds of simulators were studied to determine their
capability of producing data representative of flight. The re-
sulting data were compared with flight data from the same aircraft.
Since most of North American Aviation's simulation experience is
in the conventional type of aircraft, the compared data presented
are in up-and-away flight, with only limited data on a hover craft.

The report is published for the dissemination and application of
information and the stimulation of ideas in the area of simulation
technology with emphasis on handling qualities research.

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GROUND-BASED SIMULATION TECHNIQUES

By

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FORT EUSTIS, VIRGINIA

ABSTRACT

Many methods have been used to correlate ground-based simulators
with the actual aircraft they simulate. Comparisons of simulation with
flight in past NAA/LAD programs are presented. They include dynamic
checks, performance checks, and comparisons at the statistical level.

Favorable comparisons not only validate the particular simulator
involved but also give credence to the simulation process for future
simulators. Good correlation between simulation and flight cannot be
attributed to any one specific item. The overall handling and flying
characteristics are embodied in the simulation process, but it is the
attention to details which produces the distinguishing characteristics
of a specific aircraft.

FOREWORD

This report, prepared for the U.S. Army Aviation Materiel Labora-
tories (USAAVLABS) by North American Aviation, Inc./Los Angeles Division
(NAA/LAD), fulfills the requirements of Contract No. DA-44-177 AMC-406(T).

The NAA/LAD experience with simulators and their comparisons with
actual flight are presented herein.

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LIST OF SYMBOLS

$\dot{x}$ airplane ground speed in the direction of the runway centerline

y lateral displacement from the runway centerline

$\dot{z}_w$ rate of descent of the first wheel to touch the runway

P airplane roll rate (body axes)

Q airplane pitch rate (body axes and/or stability axes)

R airplane yaw rate (body axes)

$\dot{R}$ airplane yaw acceleration (body axes)

$V = V_T$ airspeed (total velocity vector)

V_{con} conversion velocity

v side velocity (body axes)

N_y side acceleration

N_z normal acceleration

C_m aerodynamic pitching moment coefficient

α angle of attack

β sideslip angle

ϕ Euler roll angle

θ Euler pitch angle (with respect to the ground plane)

ψ Euler yaw angle (with respect to the runway centerline)

δ_a aileron deflection

δ_e elevator or elevon deflection

δ_H horizontal stabilizer deflection

δ_w control wheel deflection

δ_r rudder deflection

δ lateral displacement (of the FS-001)

$T_{1/2}$ time to damp to one-half amplitude

q   dynamic pressure

c.g.   center of gravity

ADI   attitude direction indicator

HSI   horizontal situation indicator

SAS   stability augmentation system

IFR   instrument flying regulations

VFR   visual flying regulations

ALICE   name given to the augmented longitudinal control system of the F-107

AICS   air inlet control system

PIO   pilot-induced oscillations

HoTran   hover and transition simulator

ILS   instrument landing system

RMS   root mean square

μ_2 second moment about the mean

μ_3 third moment about the mean

μ_4 fourth moment about the mean

γ_1 skewness (coefficient of skewness)

γ_2 kurtosis (coefficient of excess or curtosis)

R&D   research and development

INTRODUCTION

Due to inherent limitations of ground-based simulators, correlation with actual flight will always be in an imperfect state. However, some good comparisons with flight had been obtained in the past, and many flight problems had been solved through the use of simulators.

The following report represents NAA/LAD's participation in the first step toward a long-range program whose ultimate goal is the categorization of all types of ground-based simulators according to their capabilities and limitations in representing the flying characteristics and handling qualities of aircraft applicable to Army missions. The objective of the subject program is to compile comparable simulation and flight test data to show what simulators can and cannot do. Since most of NAA/LAD's simulation experience is in the conventional type of aircraft, the comparison data presented are for up-and-away flight with only limited data from a hover craft.

Correlation between simulator and flight data is not limited to pilot opinion. The simulated dynamics can be objectively compared with actual flight dynamics. Even piloted handling characteristics can be objectively compared on the level of performance and on the manner in which the performance was obtained.

In the following report, some data are submitted to show what can be accomplished and what has been accomplished in the past. In the analysis and critique of the data, some plausible explanations are suggested as to why correlation was or was not obtained. Also included, wherever applicable, are our current views on the state-of-the-art in simulation, the areas in which feasible advances would extend current simulation capabilities, and the areas which are truly inherent limitations of ground-based simulation.

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Section I

PRESENTATION OF THE CORRELATION DATA

The correlation data uncovered during this program are presented in the following paragraphs, grouped according to the aircraft that were simulated. Except for the 707 landing validation program, the simulation programs conducted at NAA/LAD are directed toward aircraft design and development, and not specifically to obtain correlation data. Consequently, most of the flight-test and simulator data are obtained with various flight conditions, aircraft configurations, maneuvers, and parameters. However, in the normal course of the program, there are often some data which are taken under comparable circumstances and can be correlated. These data are collected and presented with a brief description of what they are and what significance has been drawn from them.

F-100 SIMULATION

The F-100 simulator (Figure 1) was fixed-based. Most of the studies were conducted with uncoupled modes, two-degree-of-freedom* longitudinal equations, and three-degree-of-freedom lateral-directional equations. In the majority of cases, the equations were linearized at various flight conditions under investigation; however, there were specific situations where the effects of nonlinearities were investigated. In the longitudinal mode, some studies were made with a nonlinear C_m vs α curve. Also, some nonlinear, coupled five-degree-of-freedom investigations were made.

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*In common aerodynamics terminology, the longitudinal mode refers to the motion of the aircraft in its plane of symmetry. The two-degree-of-freedom longitudinal equations are the pitching moment equation and some form of the lift equation - the two degrees of freedom of motion being rotation about the y-axis and translation along the z-axis. In three-degree-of-freedom longitudinal analysis, some form of the speed or drag equation is added to allow speed variations along the x-axis. The three-degree-of-freedom lateral-directional equations are the rolling moment equation, the yaw moment equation, and the side force equation. Hence, in five-degree-of-freedom analysis, the two-degree-of-freedom longitudinal equations are coupled with the three lateral-directional equations (forward speed is held constant), and in six-degree-of-freedom analysis, the speed equation is added to the above five.
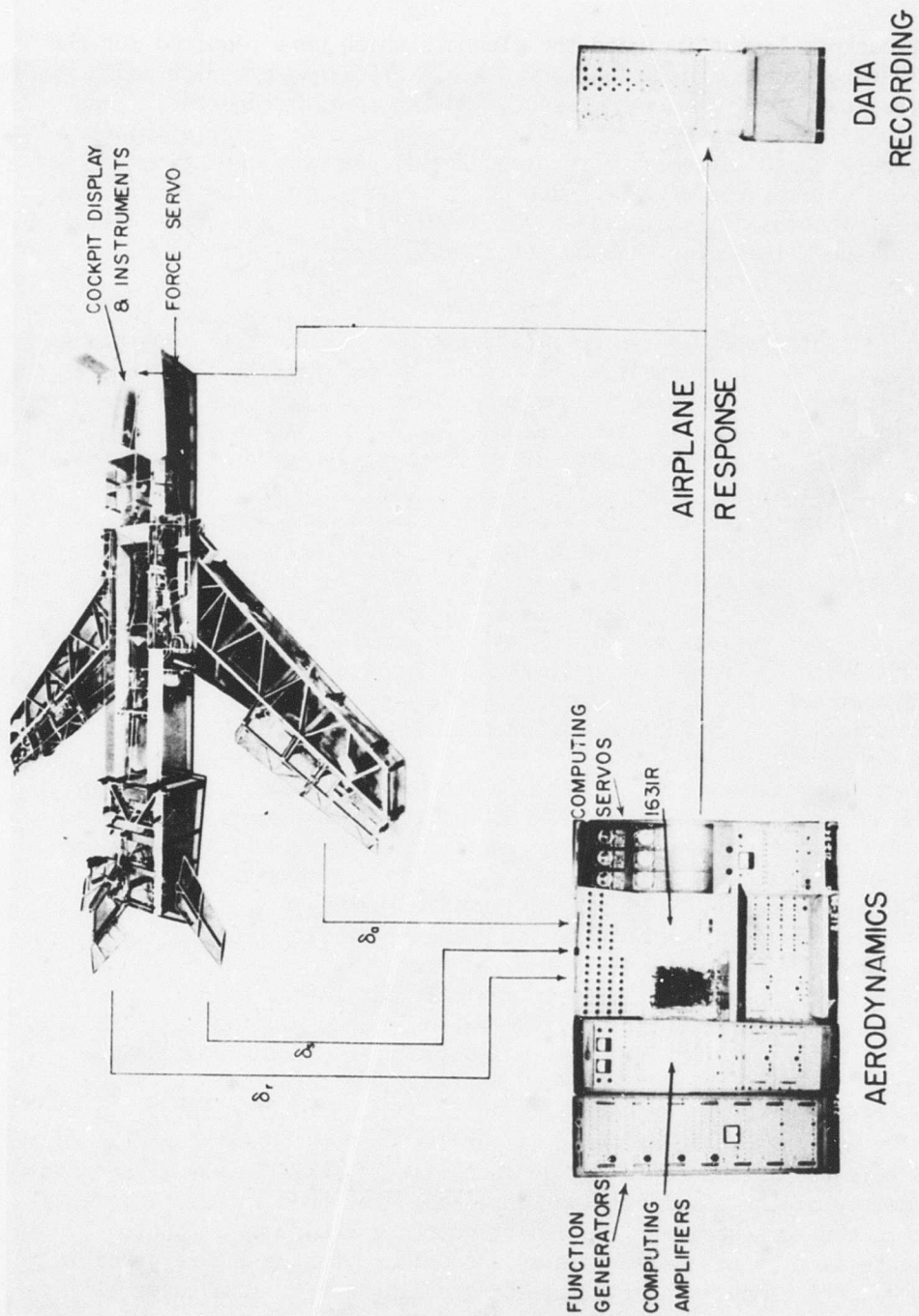
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Figure 1. F-100 Simulator.

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The cockpit layout included the elements which were required for the flight maneuvers under investigation. The interior and exterior mode lines, the instrument panel and layout, and the controls and their locations were all essentially identical with those of the actual airplane. However, only those instruments required for flight were operational; the others were only pictorially represented in their proper locations. The operational instruments included an ADI, an HSI, a turn-and-bank indicator, an airspeed indicator, a Mach meter, a "g" meter, a rate-of-climb indicator, and an altimeter.

The control system was an operational mockup of the actual airplane system. The actual hardware elements, such as the bungees, the linkages and cables, and the hydraulic valves and actuators, were configured as in the airplane. Consequently, the breakout forces, the force gradients, the friction level, and the limits of travel were representative of the airplane control system. The inertia of the control surfaces was simulated, but the aerodynamic loads and hinge moments were absent. Consequently, maximum surface rates were available at all flight conditions of the simulator.

The same test pilots flew the simulator and the airplane. The pilots' familiarity with the simulator was often accumulated during the development and checkout of the simulator. There was no prescribed program of indoctrination or determination of learn time.

Normal operation was IFR flight. On occasion, a horizon projector was used, or special scope displays were generated for specific tracking tasks. As in the airplane, only conventional aerodynamic flight was considered. Both basic aircraft control system and elementary Stability Augmentation System (SAS) were investigated. The piloting tasks were flight maneuvers and tracking tasks in up-and-away flight only.

The F-100 simulator was used extensively for flight control analysis. A distinguishing characteristic of the F-100 program was the roll coupling problem. A rather violent maneuver was encountered during a structural demonstration run of the flight-test program in which a test pilot was lost. Subsequently, the maneuver was duplicated on the simulator - practically an overlay of the salvaged flight test records. Although the data showing this comparison could not be found, it is still firmly impressed in the memory of the simulation personnel and mentioned in Reference 1. Related to the same accident, an analog computer study was conducted to investigate some solutions to this roll coupling problem and reported in Reference 2. A comparison of simulator and flight test at a safer flight condition is extracted from this report and shown in Figure 2. The intent
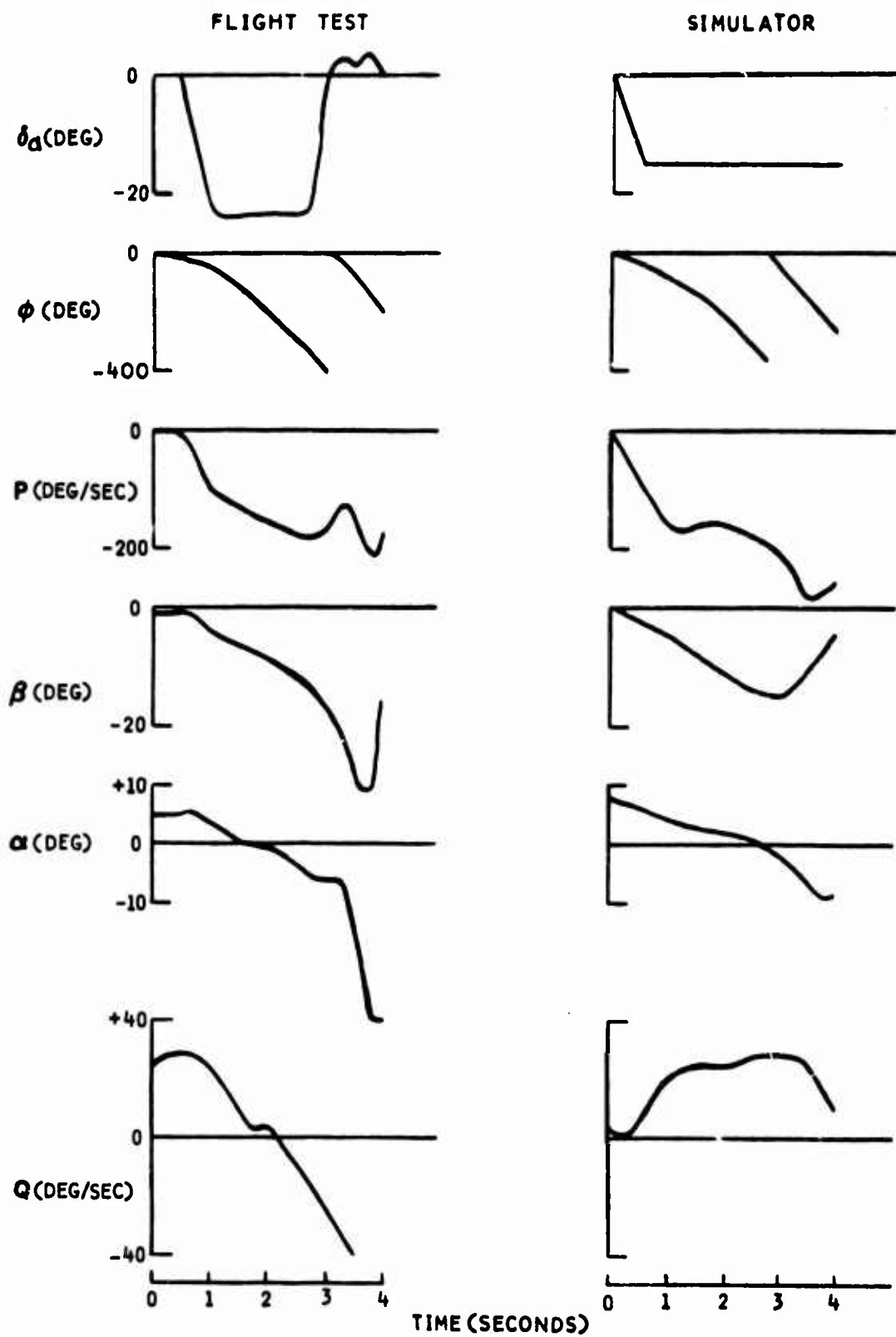
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Figure 2. F-100D Inertial Coupling Effects.

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of this comparison was not specifically to match flight test. The three axes control inputs were not duplicated on the computer to excite the dynamics, but only a simplified ramp input of aileron of approximately the same amplitude. The comparison need only show the same snap roll tendencies, in order that the study can proceed to investigate the factors which affect this problem. The fact that the same snap roll tendencies exist in both simulator and flight test suggests strongly that there is much validity in the equations - that even sophisticated dynamic charac-teristics are embodied in the analytical description of the model (which is a coupled nonlinear five-degree-of-freedom simulation in this case). Further substantiation of simulation was indicated by subsequent flight tests of the problem solution.

F-100 ZERO LAUNCH (ZEL) SIMULATION

The F-100 simulator was used for the ZEL program, in which an F-100 was configured to be launched with a rocket booster in standing takeoff. The hardware aspects were essentially the same as the F-100. However, six-degree-of-freedom equations (as reported in Reference 3) were used. Of course, the situation was quite nonlinear. Additional effects due to the rocket booster are included, such as booster angle, thrust malalign-ment, rocket burn time, and the variation of weight and inertia during the launch.

An audio cue was used to indicate the rocket boost noise, and a cable restraint on the pilot's control stick was used to indicate the "g" force. The same test pilot was used in both simulator and flight test. Due to the lack of an adequate visual display system, the VFR flight test could only be simulated with IFR flight.

The simulator was utilized to optimize the launch configuration and the launch conditions; e.g., the optimum launch angle, the booster thrust angle, the initial stabilizer angle, the effects of thrust malalignment, and acceptable tolerances. The final phase of the program was pilot train-ing in normal launches and emergency conditions or malfunctions.

A comparison of a simulator launch and a flight-test launch was re-trieved from an unpublished report and is given in Figure 3. Although the launch task is essentially the same, namely, to arrive at airborne conditions at a given altitude, the manner in which the task was accom-plished was quite different. The higher amplitude and higher frequency of stabilizer control (at $V < V_{con}$) during flight test are highly suggestive of high pilot gain. In general, simulators are much safer
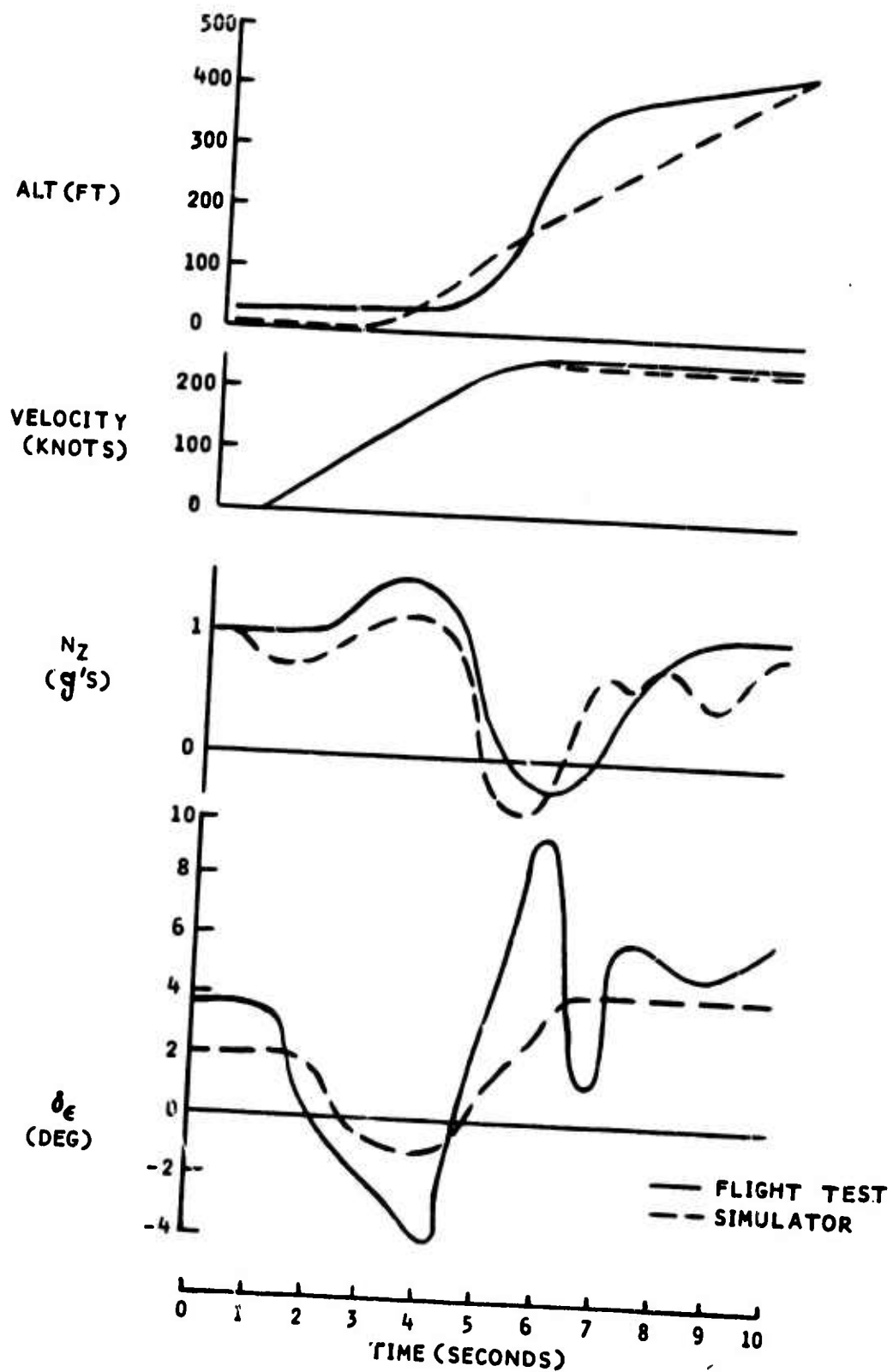
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Figure 3. F-100 Zero Launch Comparison.

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than actual flight, and in this sense quite unlike the airplane. Since the ZEL simulation did not have cockpit motion and visual display of the terrain, it may be conjectured whether the extra cues can add sufficient realism to induce the normal anxieties of flight.

Favorable comparison was indicated by the pilot's comments. During the pilot training phase of the simulator program, a malfunctioning condition of the airplane with the empty booster case attached was investigated. With this load at the aft end, the simulated airplane was found to be statically unstable; however, the pilot could control it in the simulator. On the second launch of the flight-test program, the empty booster case would not separate, and his comments were: "No problem in maintaining positive control of the aircraft with the empty booster case still attached was experienced. Simulator studies of this condition gave a very accurate picture and are considered to have been most valuable." This indication of correlation occurred in an airborne condition in which dynamic and handling characteristics of the airplane were involved.

F-107 SIMULATION

The F-107 simulator is shown in Figure 4. It is quite similar to the F-100 simulator, except configured for a different airplane. The major improvement is in the computer equipment used to mechanize the equations of motion.

The F-107 simulator was fixed-based. Although some five-degree-of-freedom nonlinear analyses were conducted, most of the simulation activity was accomplished with linearized two-degree-of-freedom longitudinal and three-degree-of-freedom lateral-directional analyses.

The cockpit was like the airplane, with the same layout of instruments and switches. However, only the flight instruments were operative; e.g., ADI, HSI, rate-of-climb, airspeed, Mach, turn and bank, and altimeter. The control system is an operational mockup of the airborne system on which the airborne hardware was developed, including the components of the augmentation system.

Engineering test pilots flew both the simulator and the airplane. As in other conventional airplanes, the piloting tasks were in up-and-away flight.
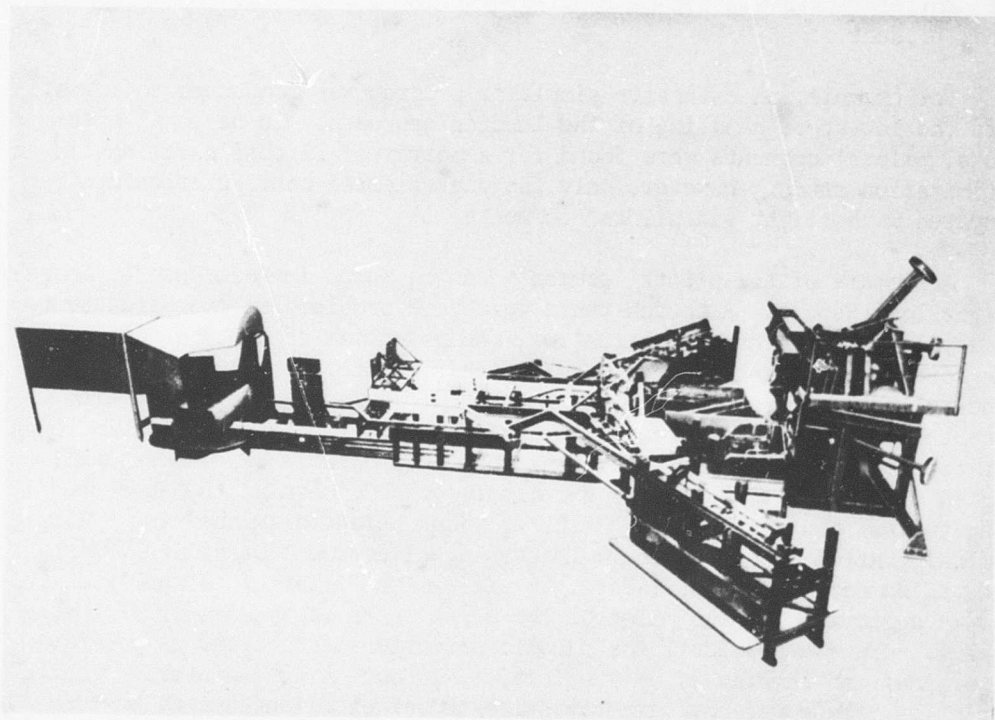
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Figure 4. F-107 Simulator.

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The literature search of F-107 data was rather disappointing. Although much data were retrieved, little or virtually no data were found for the same simulator and flight-test conditions. The primary difficulty was in locating simulator data. Although extensive simulation programs were conducted in the design and development of the flight control system, essentially only the final product was preserved. Hence, the only correlation available is implied by pilots' comments concerning the final product.

For example, an extensive simulator program was conducted to investigate the low-speed handling of the landing approach. In personal notebooks, pilots' comments were found for a matrix of 25 configurations in an optimization study. However, only the one selected configuration can be compared with flight via pilots' comments.

A summary of the pilots' comments can be found in Reference 4, Phase I Flight-Test Report. Although there were some problems in the hardware to be resolved in a prototype situation, the essential comments concerning the control situation as developed on the simulator were quite favorable. Concerning the approach and landing, "No difficulties were encountered except in lateral control in rough air .... The yaw damper action in rough air appears to aggravate the lateral control problem. Yaw damper functioning in other than rough air is excellent...." Concerning the augmented longitudinal control system, "ALICE provides potentially the finest longitudinal control in existence." Concerning directional stability, "With the yaw damper 'off', the lateral directional oscillation is poorly damped and is aggravated by the pilot to the point where it appears to be Dutch Roll.... Yaw damper 'on', the dynamic directional stability is positive throughout and damping is very effective." Concerning maneuvering characteristics, "Maneuvering characteristics appear excellent due to the constant 3.75 pounds stick force per 'g' gradient which holds throughout the range from .5 Mach to Vmax afterburner. Feel is also excellent due to the constant 3/4-inch stick motion per 'g' at all speeds above .5 Mach."

The excerpts of the pilots' comments on the F-107 flight-test program show implicitly the favorable comparisons between simulator and flight test. The control system developed and optimized on the simulator was well regarded on the actual airplane, thus implying at least adequate simulation. There were some hardware problems (such as dead band) which were resolved on the operational mockup of the control system used as part of the simulator under simulated flight conditions. It is also interesting to note the objections to rough-air operation of the yaw damper, because rough-air operation had not been investigated on the simulator. Subsequent to this program, rough-air simulation was developed.

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X-15 SIMULATION

The X-15 simulator shown in Figure 5 was also fixed-based. Although many simplified analyses were made during the airplane development phase, the final product was a full-flight-regime, nonlinear, six-degree-of-freedom simulation. The simulator cockpit was fully instrumented like the airplane. The control system was an operational mockup of the control system including the stability augmentation system. In addition to the conventional controls, the X-15 had a side-arm controller and a reaction control arm, which were both also in the simulator. The X-15 test pilot also flew the simulator extensively, but only in IFR flight.

Comparisons between simulator and flight test had been obtained at different levels of simulation. During the first and second powered flights of the X-15 ship No. 2, several pulse-type maneuvers were performed to check the aerodynamic stability of the system with and without the SAS. The period and damping of the airplane oscillations were compared with the predicted values of the simulator. These comparisons were extracted from Reference 5 and are presented here in Tables I and II. In the first powered flight (Table I), the maneuvers were performed with SAS operative. In the second powered flight (Table II), the pitch and yaw channels of SAS were engaged in the first three flight conditions (roll channel disengaged), and the SAS was disengaged for the pulse maneuvers of the fourth flight condition. In general, the comparisons were found to be acceptable except for the Mach .95 condition. Traditionally, the transonic region has been the most difficult flight regime to accurately simulate in a six-degree-of-freedom simulation. Because of the rapid change of aerodynamic characteristics with Mach number, small errors normally within the confidence limits of standard engineering procedures can result in significant changes in aircraft dynamics. Hence, the seemingly large difference in the longitudinal short period at Mach .95 can be caused by small errors in any one or more of the items, such as the data reduction of wind tunnel tests, the flexibility corrections of a nonrigid wing, the manufacturing tolerances of the airframe, the estimation of the c.g. location in flight, the precision of the mechanizations of the aerodynamic nonlinearities, or the difference between actual atmospheric conditions and the simulated "standard day."

The frequency and damping of the airplane modes can be viewed as the eigenvalues of the stability matrix of the equations of motion. The matching of frequency and damping then shows the adequacy of the equations of motion and the input data, such as mass, inertia, aerodynamics, and other peripheral data. Hence, except for the Mach .95 case, the spot check of the stability characteristics at various flight conditions
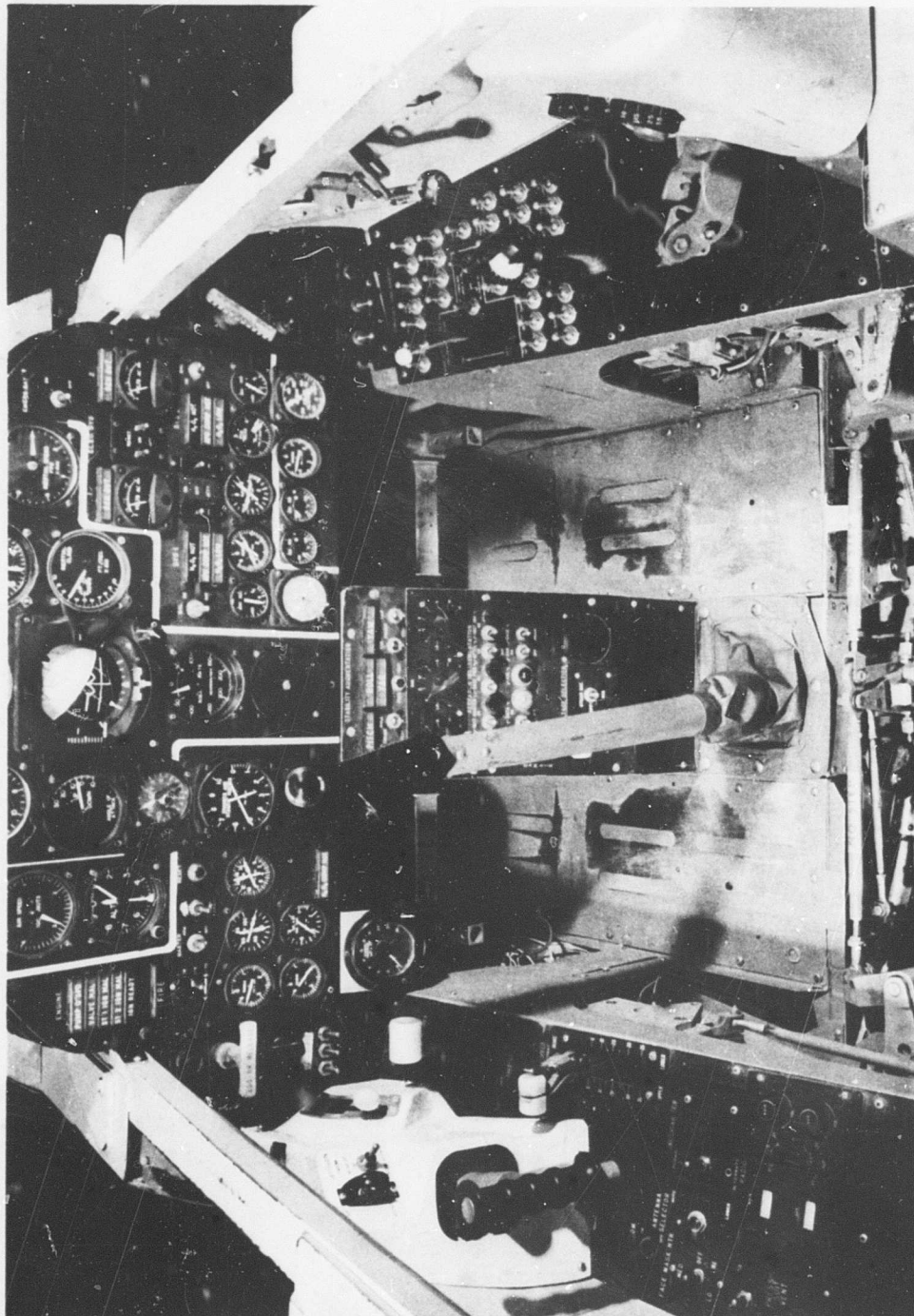
Figure 5. X-15 Simulator.

TABLE I

X-15 PERIOD AND DAMPING - FIRST POWERED FLIGHT

	Mach	Altitude (ft)	Period (sec)		T½ (sec)		Weight (lbs)	q (lbs/ft²)	V (ft/sec)	(deg)
			Flight	Analog	Flight	Analog				
PITCH PULSE	1.13	45,350	2.13	2.10	0.70	0.70	27,700	276	1084.3	6.2
	1.80	50,200	1.22	1.55	0.95	0.65	19,150	548	1722.7	2.7
	0.95	47,400	2.00	3.10	0.90	0.85	15,070	175	900.2	4.5
YAW PULSE	1.18	47,000	1.89	2.26	0.95	0.90	27,500	277	1131.6	5.2
	1.74	50,600	1.56	1.70	0.70	0.65	19,400	510	1672.1	2.7
	0.95	47,800	3.00	2.80	1.48	1.18	15,100	170	908.6	4.5
LAUNCH	0.80	37,700					32,762	197	776.9	0
BURNOUT	2.09	47,400					15,700	845	1992.5	2.5
TOUCHDOWN	0.28	2,350					13,991	110	320.9	9.0

TABLE II

X-15 PERIOD AND DAMPING - SECOND POWERED FLIGHT

	Mach	Altitude (ft)	Period (sec)		$T_{\frac{1}{2}}$ (sec)		Weight (lbs)	q (lbs/ft²)	V (ft/sec)	(deg)
			Flight	Analog	Flight	Analog				
PITCH	1.04	41,300	1.85	1.70	0.80	0.70	28,450	280	1013.4	11.2
	1.45	49,800	1.45	1.85	0.80	0.80	21,850	365	1378.2	11.2
PULSE	1.65	50,200	1.25	1.65	0.65	0.60	15,270	466	1570.7	1.5
	0.88	37,000	2.20	2.65	1.25	1.40	15,050	243	864.7	5.0
YAW	1.16	51,500	1.80	1.78	0.60	0.70	19,700	342	1384.9	6.0
	1.72	52,300	1.50	1.65	0.50	0.55	15,300	450	1621.4	0.5
PULSE	0.93	42,100	2.25	2.35	1.00	1.02	15,200	212	901.9	3.8
	0.85	35,500	2.15	2.18	2.70	2.72	15,000	249	844.5	5.2
LAUNCH	0.82	40,700					32,275	180	743.1	0
BURNOUT	1.81	54,600					15,370	450	1705.8	5.2
TOUCHDOWN	0.28	2,200					13,960	102	278.7	7.0

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adds confidence to the simulation. This check does not include the excitation function or the control power, but only affirms the adequacy of the basic airplane dynamics.

Another check of the airplane dynamics is given in Figure 6, extracted from Reference 6. During the landing flareout of the first glide flight, an undesirable PIO condition was encountered. The pilot perceived that he was approaching the ground rather rapidly and proceeded to arrest the rate of descent, using the side stick control. The phasing between the control inputs and the dynamic response perceived by the pilot was such that an oscillatory condition was sustained for about 20 seconds. During the investigation of this problem, the flight-test records were duplicated on the simulator. The time history of the horizontal stabilizer position was extracted from the flight-test records and fed into the simulator. The resulting simulator response was compared with flight test. The comparison as shown in Figure 6 indicates a high degree of correlation. This transient match is actually quite similar to the stability check. Instead of the response to a pulse input, the response to a continuous input is used. So, in addition to the basic airplane dynamics, it also checks the excitation function and possibly the cumulative effects of small errors.

A major emphasis of the X-15 simulation program was pilot training and mission planning. As stated in Reference 7, "... each pilot spends approximately 20 hours in simulation preparation for 10 minutes of flight time." The flight plan of the X-15 is developed on the simulator. Two comparisons of simulator predictions with actual flight mission profiles are presented in Figures 7 and 8 (taken from Reference 6). Figure 7 shows a maximum-speed flight, and Figure 8 shows a maximum-altitude flight. In contrast with the comparisons of airplane dynamics, these comparisons show correlation at the performance level of the overall mission profile. The entire simulation complex is operative in generating the mission profile; the pilot senses the response of the airplane, compares it with the flight plan, and makes the necessary maneuver and/or correction.

XB-70 SIMULATION

The XB-70 simulator shown in Figure 9 was fixed-based. The dynamics of the airplane were simulated in all six degrees of freedom. The cockpit was a mockup of the actual cockpit. with the same interior and exterior mold lines, and was fully instrumented. The instrument layout

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FLIGHT DATA

ANALOG DATA

$\sim$Q
DEG/SEC

α
$\sim$DEG

N_Z
$\sim$g
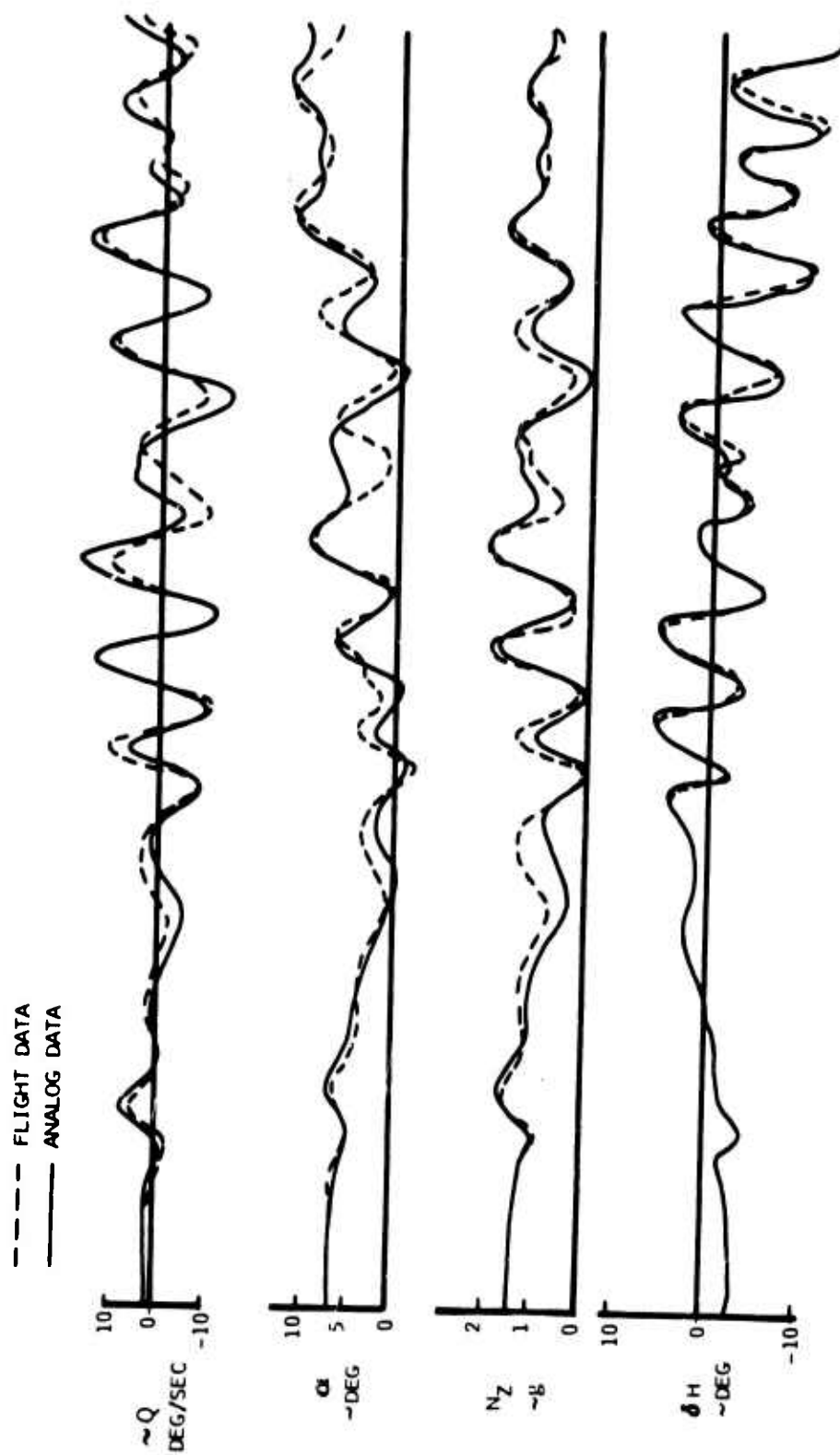
δH
$\sim$DEG

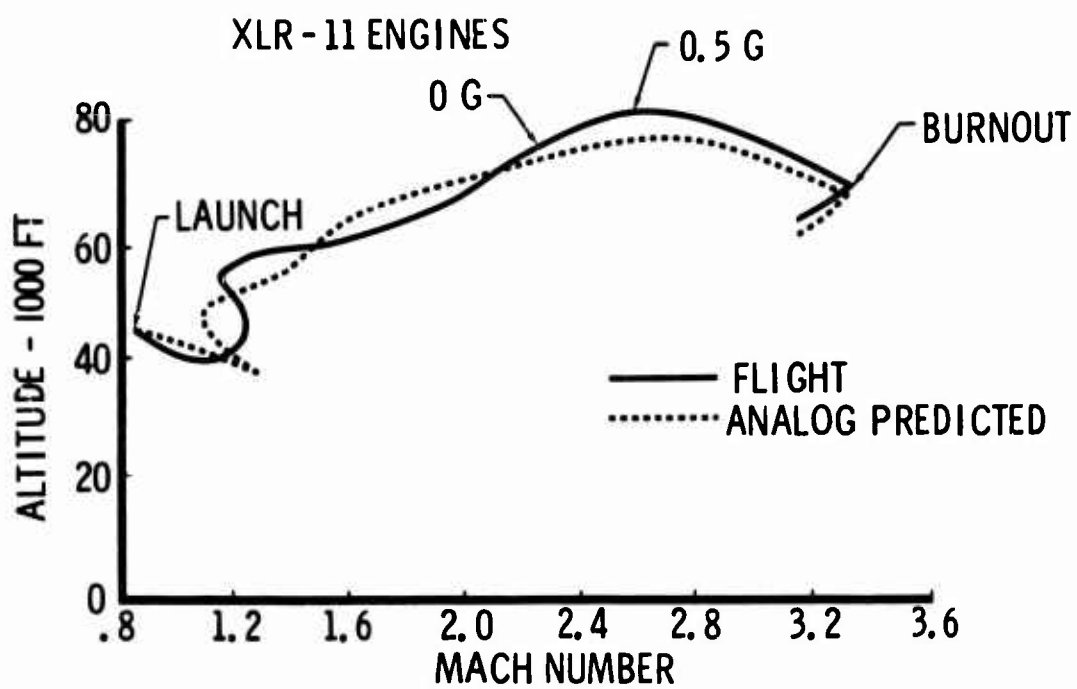Figure 6. X-15 Landing Flareout Comparison.
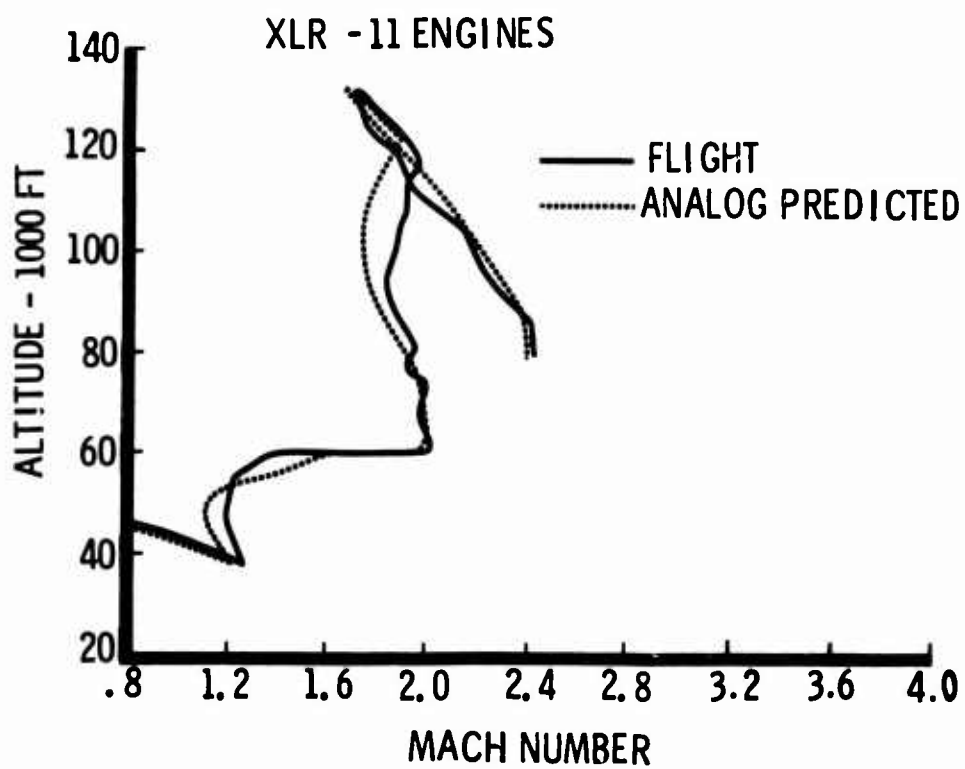
Figure 7. X-15 Maximum-Speed Flight.

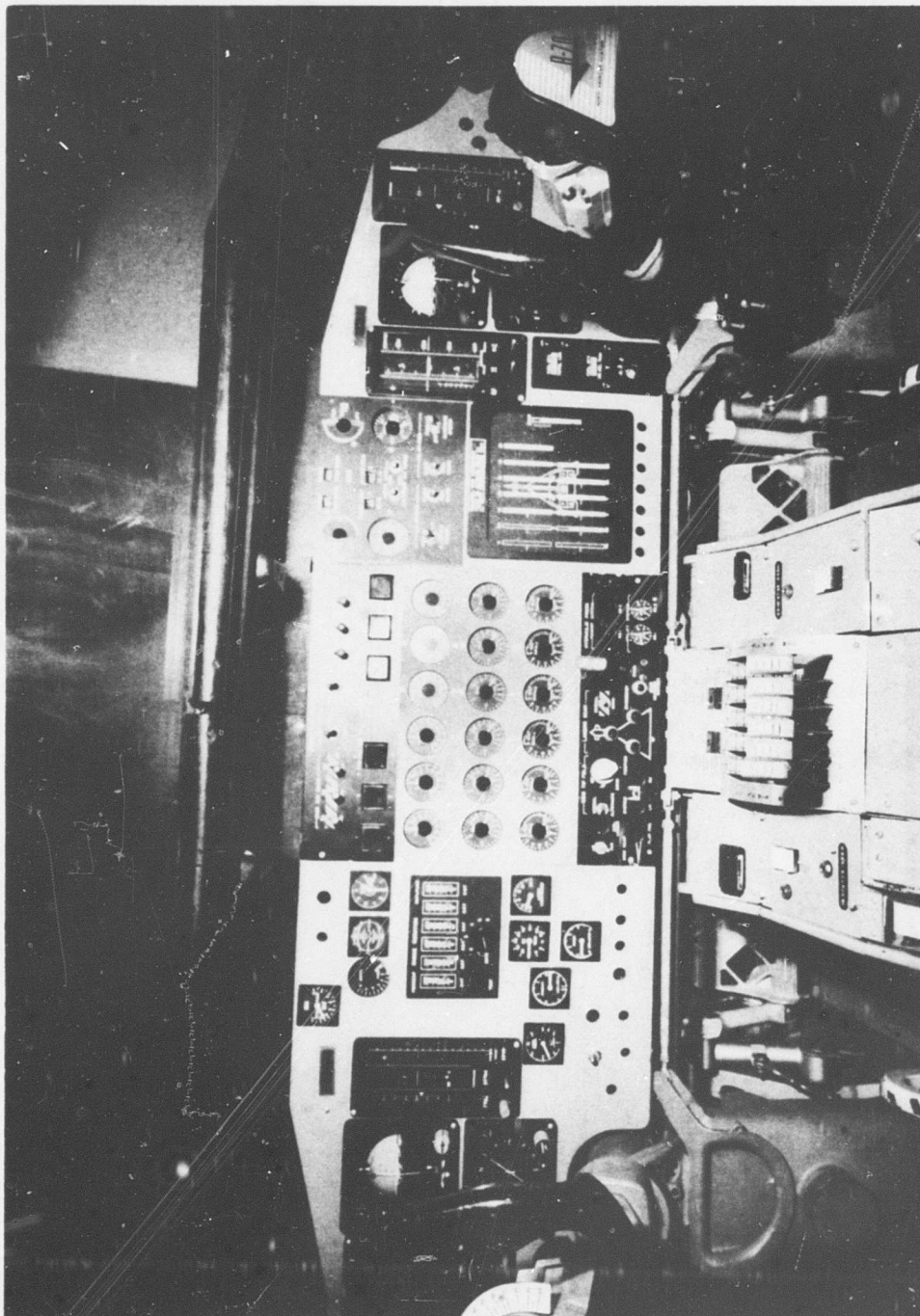Figure 8. X-15 Maximum-Altitude Flight.

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Figure 9. XB-70 Simulator.

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was identical with that of the airplane. The instrument panel could be modified and changed to correspond with either ship No. 1 or ship No. 2. The flight instruments, including the airborne tapeline instruments, the engine instruments, and the instruments associated with the AICS, were all operative.

For takeoff, landing, and other low-altitude studies, a closed-circuit television display system was used. The display was servoed in all six degrees of freedom, and the terrain model represented an area 10 miles long by 4 miles wide. Hence, the simulator had both VFR and IFR capability.

The control system was an operational mockup with actual hardware like the airborne system, including the SAS. The SAS could be engaged and disengaged from the simulator cockpit as in the airplane.

The same test pilots flew both the simulator and the airplane. Many aspects of the airplane development were accomplished on the airplane. The simulator was also used for pilot training and flight plan rehearsal.

The XB-70 simulation was a rather formidable task because of its wide flight regime, folding wingtips, and air inlet system. The computerization of the complete six-degree-of-freedom simulation is reported in Reference 8, which shows how the complex XB-70 system was mechanized with a reasonable amount of computing equipment.

In general, the correlation between flight test and simulation is satisfactory. The IFR simulation is better than the VFR conditions, and the airplane is easier to fly than the simulator.

The initial landing investigation on the XB-70 simulator was not considered satisfactory. The landings were rather inconsistent, and the average rate of descent at touchdown was considered excessive. Subsequently, the XB-70 landing mechanization was integrated with the movable transport cockpit for a brief study. The landings with the transport cockpit were much more consistent, and the average sink speed at touchdown was more reasonable. Although the study was brief and results were not conclusive, the strong indication is that the additional in-flight cues of the transport cockpit were significant. The cockpit motion presented some kinesthetic cues which were absent in the static XB-70 simulator, and the visual display configuration of the transport cockpit produced a sharper image than on the XB-70 simulator. The landing

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condition was reinvestigated on the XB-70 simulator after some improvements were made on the visual display presentation, and the landing performance was also improved.

The importance of the visual cues was also suggested by the flight-test results. With the actual visibility of the real world, the flight-test landings were consistently very smooth. Although the correlation between simulator and flight test was not impressive at all in this landing condition, the pilots did indicate some merit of the landing simulation in their comments. The dynamic characteristics of the airplane in the landing approach were faithfully simulated, and they did prepare the pilots for the control situation of the airplane. In reiteration, the pilots commented that it was the visual display presentation in the simulator which was inadequate for determining the altitude for flare point and for judging where the airplane was with respect to the ground.

The comparison of the dynamic characteristics is quite satisfactory. Figures 10 and 11 compare simulated dynamics with airplane dynamics for aileron and rudder inputs. The simulated dynamics were generated on the complete six-degree-of-freedom simulation. In these initial comparisons, simplified simulator inputs were used to check the overall response. Figure 12 shows a more sophisticated comparison in which an attempt was made to duplicate the pilot input on the simulator. This comparison was taken from an analog computer study to evaluate the adequacy of the predicted aerodynamics. A linearized three-degree-of-freedom mechanization was used for this side study. Two aerodynamic coefficients were significantly changed in order to obtain this match. The predicted aerodynamics produced response traces similar to those in Figure 12, except that the amplitude of the β trace was too low. Adverse yaw was introduced through $C_{n_{\delta_a}}$ in order to increase the β amplitude. Then $C_{l_{\delta_a}}$ was increased in order to nullify the dihedral effects of the higher β amplitude. The drift in the bank angle trace was probably due to minor differences in the initial accelerations. Although the task of the side study was to match flight test without regard for rationalizing the changes required, previous experience with the XB-70 simulation program offers some possible explanations.

On the XB-70, the elevon panels are operated together for pitch control and differentially for roll control. Due to the nonlinear aerodynamic characteristics of the panels, both $C_{l_{\delta_a}}$ and $C_{n_{\delta_a}}$ are functions of the elevon position from which the differential operation is superimposed. Hence, errors in estimating the airplane weight or c.g. location can cause differences in the elevon trim position which in turn

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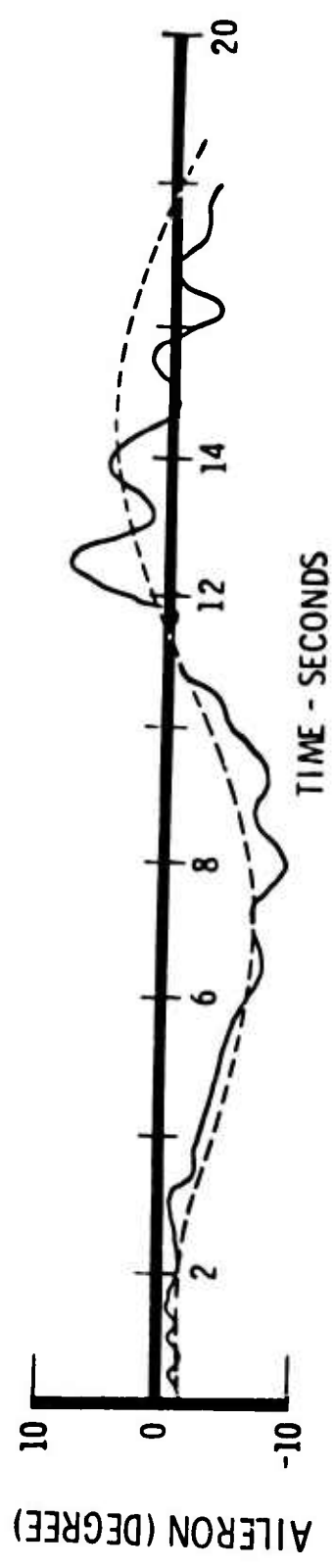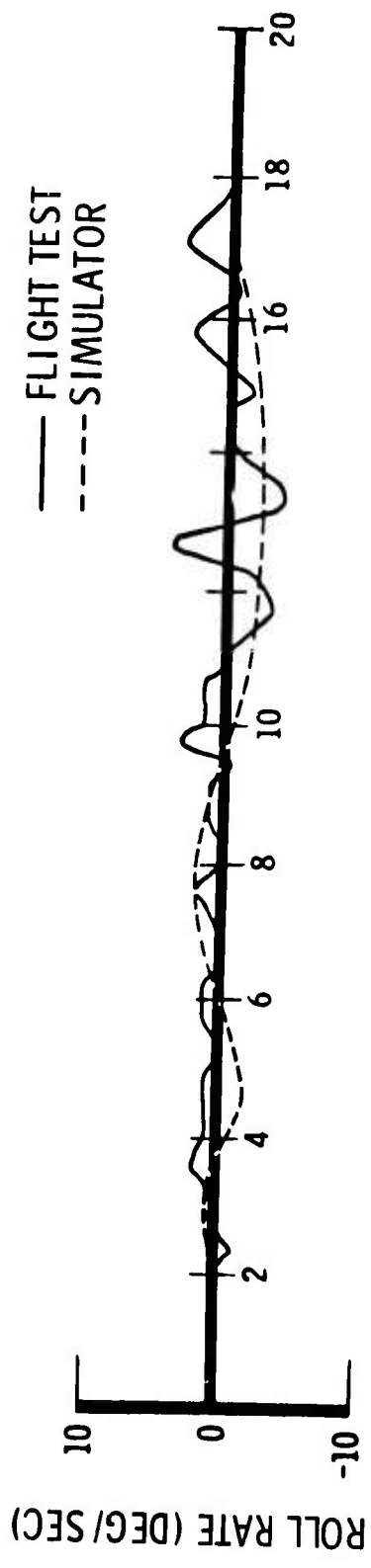Figure 10. XB-70 Time History of an Aileron Input.

21

FLIGHT TEST
--- SIMULATOR

SIDESLIP (DEGREE)

SIDE ACCELERATION (g's)

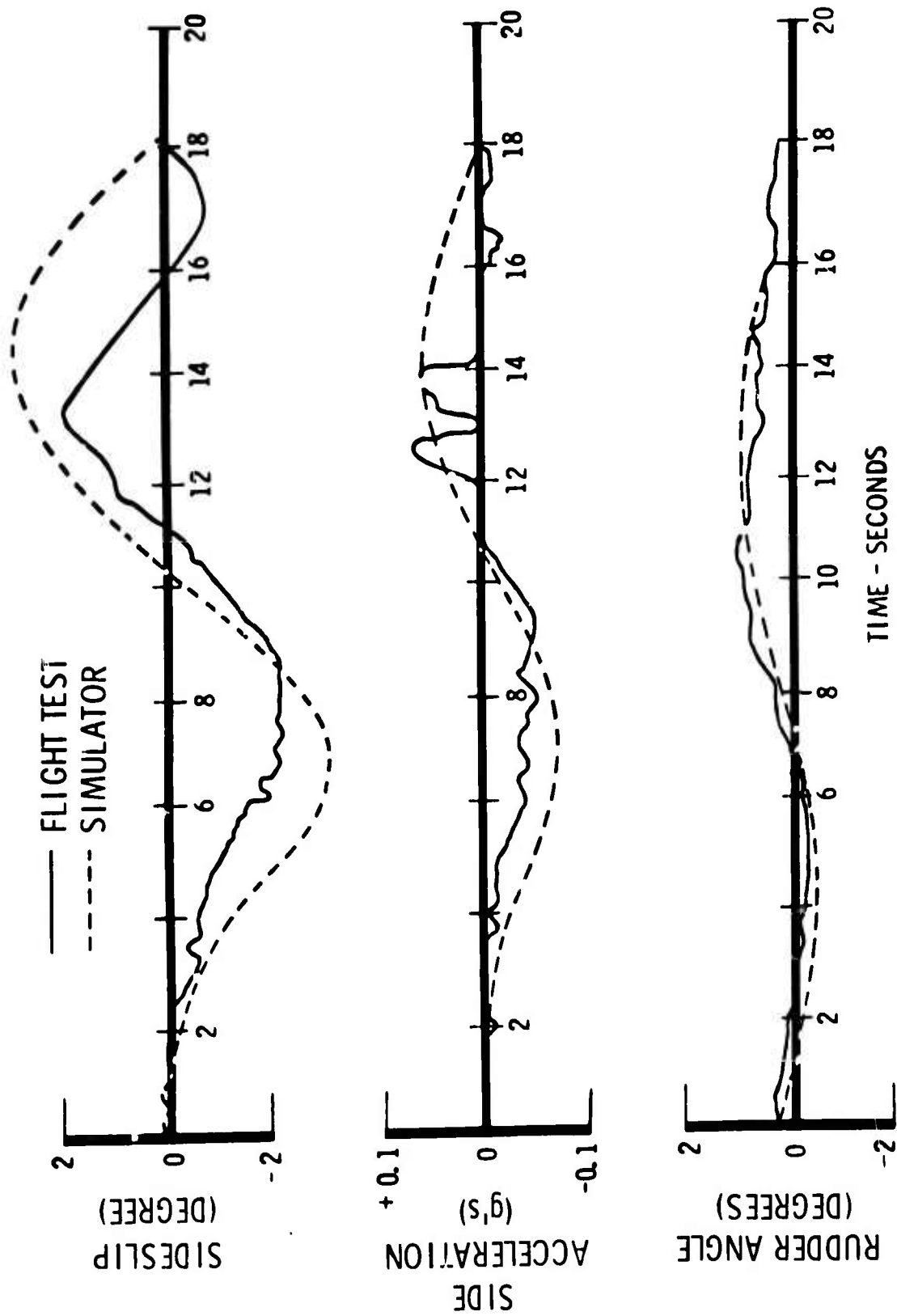RUDDER ANGLE (DEGREES)

TIME - SECONDS

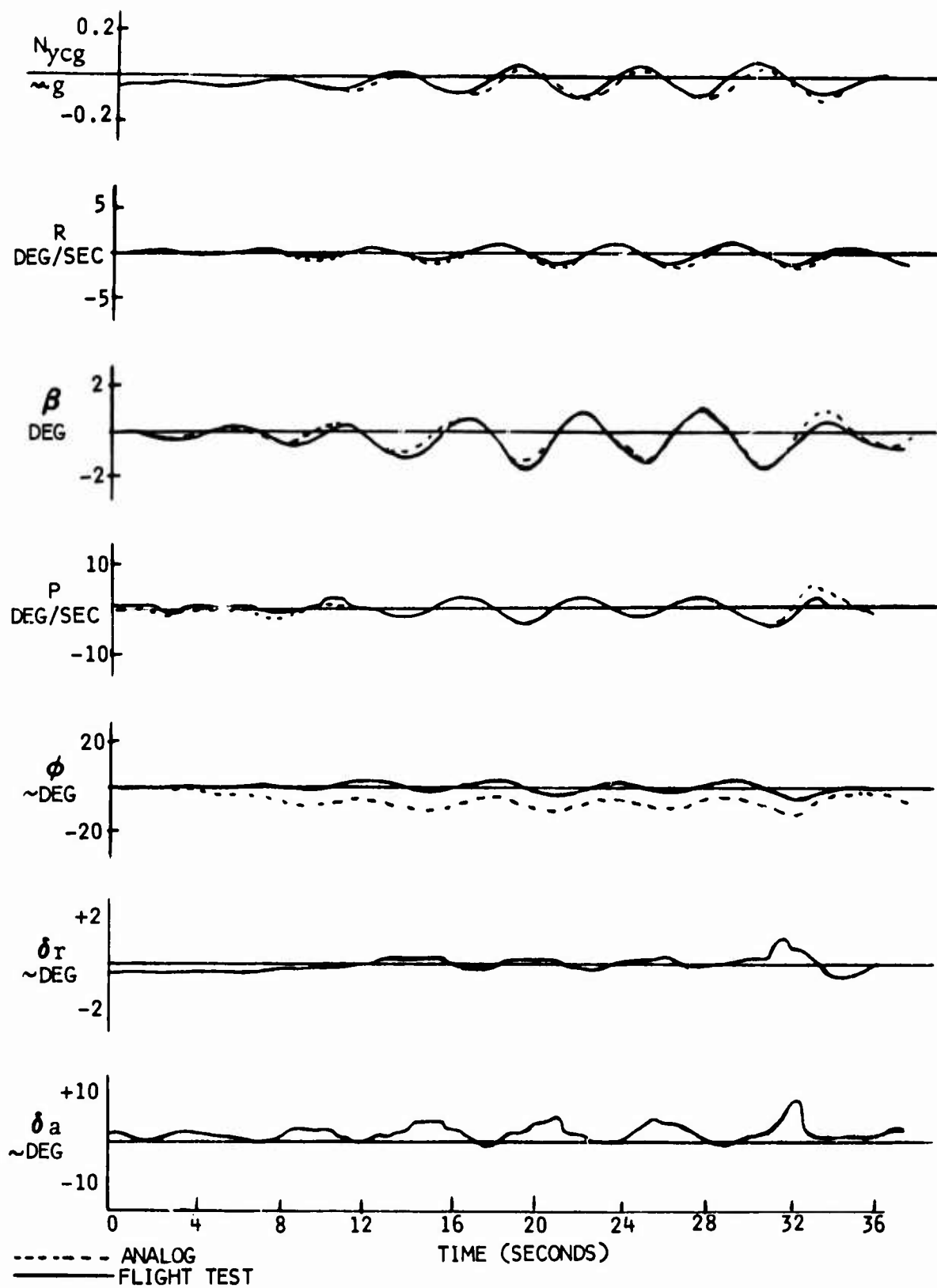Figure 11. XB-70 Time History of a Rudder Input.

Figure 12.   XB-70 Flight Test Match.

affect the roll control characteristics. However , experience with syn-
thesis of flight-test transients to obtain aerodynamic stability deriva-
tives has shown that the solution is not unique. There are other combina-
tions of changes that will produce a similar match.

Another type of correlation is available on the level of the pilot
ratings of the airplane dynamic characteristics. The Cooper rating scale
was used in evaluating some maneuvers in an SST related study conducted
on the XB-70 simulator. The simulator rating shown in Figure 13 is taken
from this study with flight-test rating overplotted. The simulator data
and the flight-test data were taken under different conditions except for
two points: Mach .4 at 5000 feet and Mach 3.0 at 70,000 feet. In both
these conditions, the pilot rated the airplane better (lower number) than
the simulator.

At the low-speed condition, a major deficiency of the simulator is
cockpit motion. The airplane attitude and its variations contain motion
cues which have been considered to be important in low-speed flight. At
high-speed flight, the major lack of the simulator is the "g" feel. Be-
cause of the high speed, a change in pitch attitude barely discernable
on the ADI can easily be felt. Because the motion cues are absent, the
pilot is forced to fly the simulator with the "g" meter and rate-of-
climb indicator.

Recognizing the inherent limitations of a static simulator, the
XB-70 simulation can then be used to perform the tasks for which it was
designed. The dynamic characteristics of any flight conditions can be
investigated conveniently, separately, or in the context of a total
mission.

TRANSPORT SIMULATION

A landing simulation program was conducted on the transport simula-
tor shown in Figure 14. The transport simulator has a moving base with
two degrees of freedom: pitch and roll. The pitch travel ranges from
+16 to -18 degrees and the roll travel is ±15 degrees. The small
hydraulic valves used for low-performance transports permit a maximum
pitch motion rate of 2 degrees per second and a roll rate of 4 degrees
per second. Since there is vertical translation associated with the
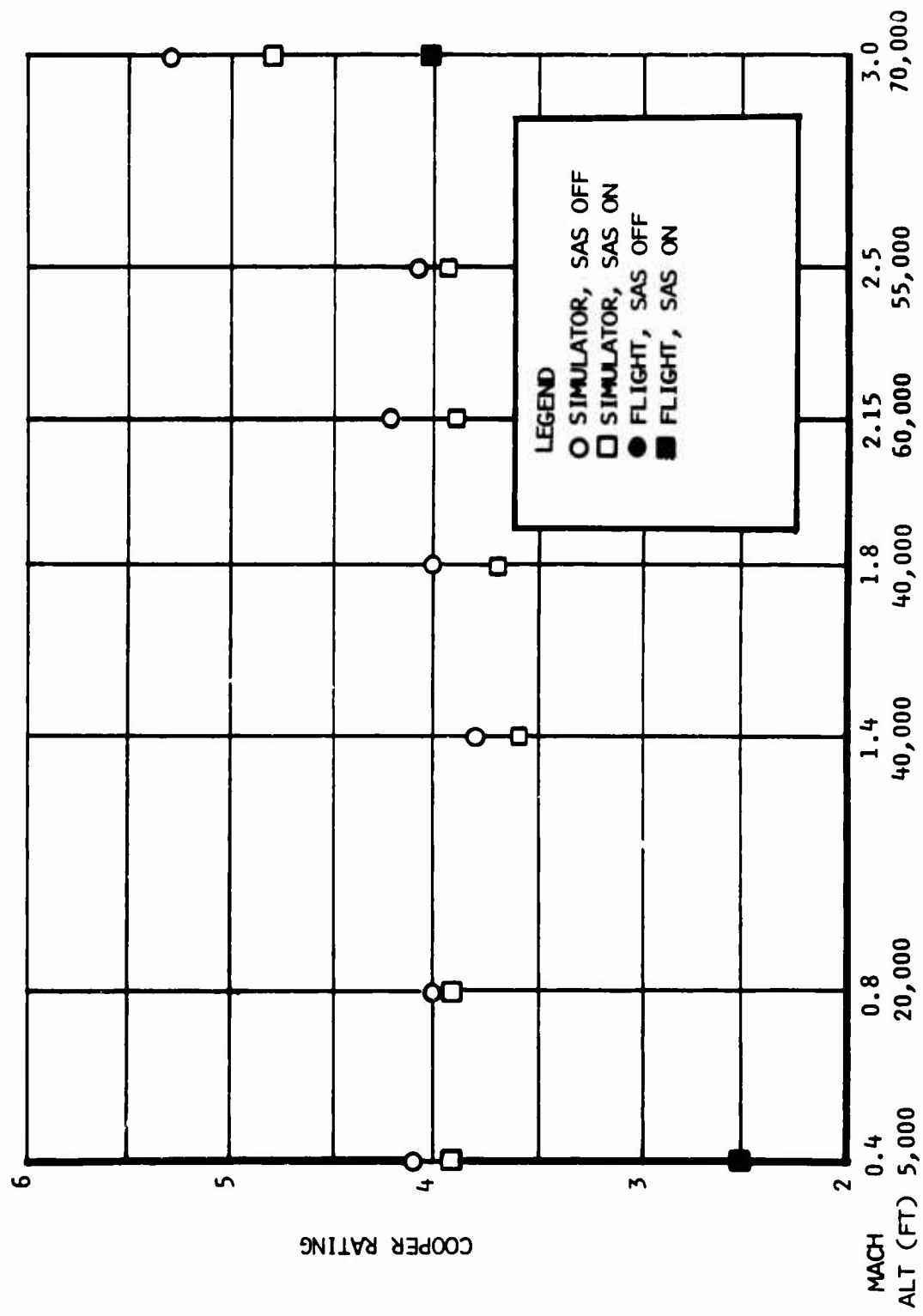pitch motion, an increment of 1/2 g is available for landing impact.

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Figure 13. XB-70 Pilot Opinion Ratings.

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TERRAIN DISPLAY

MOVING COCKPIT
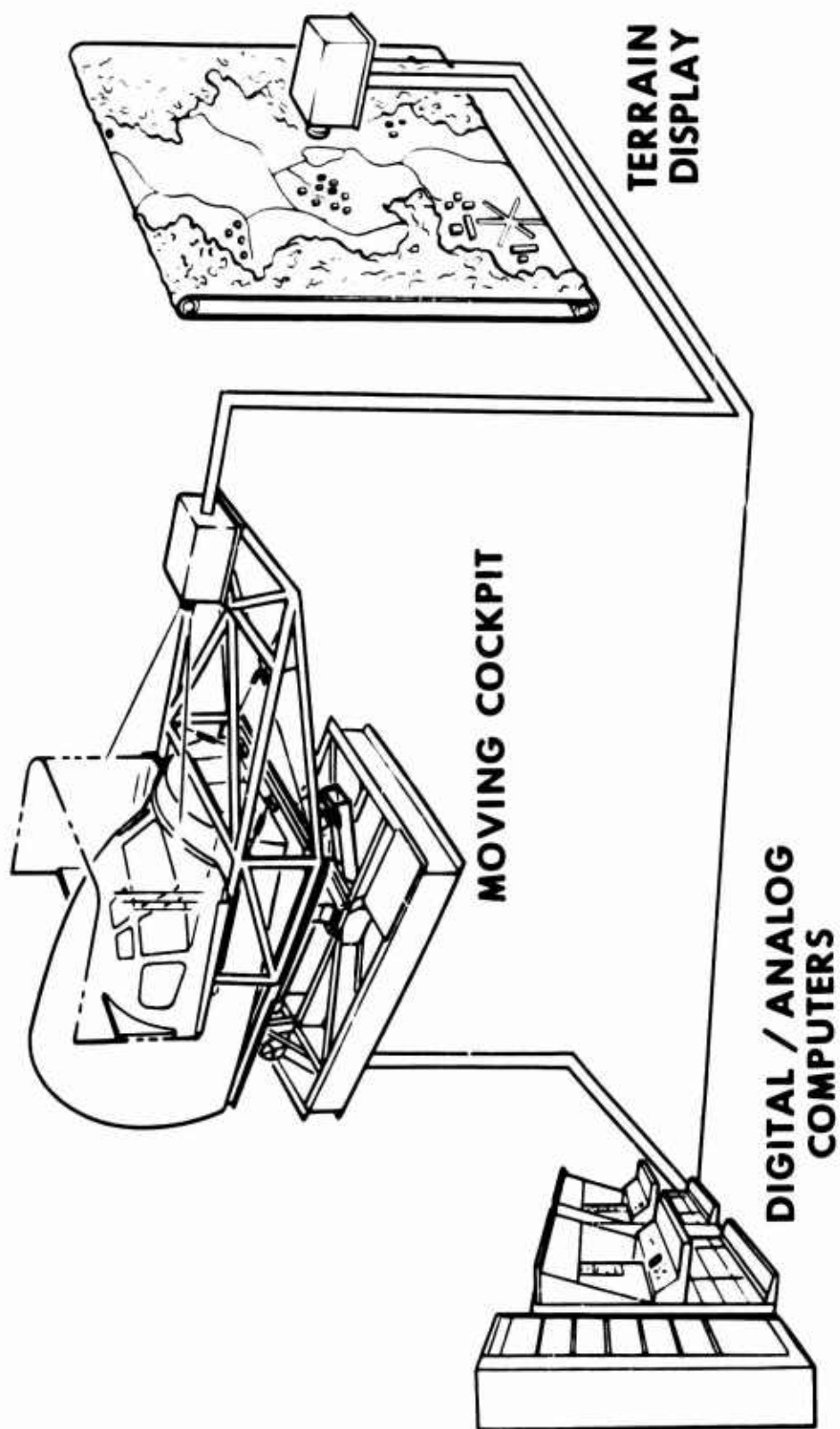
DIGITAL / ANALOG COMPUTERS

Figure 14. Transport Simulator.

The dynamics were mechanized in all six degrees of aircraft freedom throughout the landing flight regime. The nonlinearities of the data were mechanized as precisely as possible. Extra circuitry was used to increase the resolution of the analog portion. A digital computer was used to increase the overall precision.

The cockpit is a replica of the Boeing 707, built from Boeing's mockup drawings. Since the instrument layouts differ among air carriers, a layout representative of a particular model was duplicated. Because of its availability, the Collins FD-105 flight director instruments were used; however, it was later discovered that most of the pilots were not familiar with the Collins system. Only the flight instruments of the pilot's station and the engine instruments of the center panel are operative. Instruments not used by the pilot for the landing task were silk screened in at the proper locations; for example, the overhead panel, the copilot's panel, and the center pedestal.

A closed-circuit television network was used to televise a picture of the model airport with surrounding terrain. The visual display system was driven by computer signals in all six degrees of freedom. The model represented a 10-mile-long by 4-mile-wide terrain. The equivalent altitude range is from 12 feet to 1400 feet. The angular range is +25 to -10 degrees in pitch, ±70 degrees in roll, and several turns in yaw.

The flight control system was simulated with hydraulic force servos, and calibrated to match the design curves. Adjustments were made to match the breakout forces and the force gradients. The airborne hardware of the center pedestal was installed in the simulator, and the position of the throttles was sensed by the computer. The flap handle was also operative.

Airline pilots on regular runs with the Boeing 707 were used in the program. Since the pilots were already familiar with the airplane, no extensive indoctrination or learning time was permitted by the contract. However, the pilots were briefed on the purpose of the program and were given five check landings, because most of them were not familiar with the Collins flight director system and the visual display.

Both IFR and VFR flight were available. The recommended procedure was to fly IFR using the flight director ILS glide slope and localizer down to the middle marker and then to proceed with VFR to touchdown. Because of the unfamiliar Collins flight director system and other personal habits, the pilots were not restricted to the recommended procedure. Flap and throttle management also differed among pilots. The pilots were

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requested to land the simulator as they normally do in the airplane. The basic aircraft control system and a yaw damper were in operation. The pilots were requested to use the yaw damper as they would normally do in actual flight. The point at which the dampers were turned off varied among air carriers. The piloting task was normal landings on commercial, prepared runways. Some maneuvers were required to line up the approach.

This program conducted specifically for correlation purposes is reported in Reference 9. (However, the contractual agreements only called for the generation and presentation of the simulator data. NAA/LAD was directed not to draw any conclusions in the final report, but to submit the simulator data for correlation with flight data by the customer.) The means for determining the degree of validity of the simulator was to simulate an existing airplane (Boeing 707) and to compare the landing impact characteristics of the simulator with those of the actual airplane. The actual airplane data were reduced by NASA from photographs of actual commercial landings at Los Angeles and New York airports. Since the correlation data were to be compared on the statistical level, it was hoped that the 10 airline pilots representing four air carriers were representative of the actual flight data.

The approach of the subject simulation was to maintain a high level of accuracy throughout the entire simulation system by adhering strictly to the given data, utilizing the maximum accuracy capabilities of the computer equipment, providing a visual display picture with accurate optical perspective throughout the entire landing trajectory, and including some environmental details which enhance the "in-flight" realism of the simulator. To preserve the predictive characteristic, data updated by flight test were purposely excluded.

Although all the raw data generated by this program were shipped to the customer, much of the data can be found in Reference 9, which is in three volumes. Volume I is the summary report. Volume II contains tables of statistical properties of the data and probability of exceedance curves. Volume III contains landing trajectories with corresponding time histories of selected airplane parameters. A sample of the results of this program is presented in Figures 15 through 20 and in Table III. Setup 2211 is chosen as a representative configuration. It has the lighter weight which is more representative of the landing conditions, an aft c.g. location, the normal ground effects, and the unboosted rudder of the earlier models which were photographed by NASA.

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Figure 15.   Sample Trajectory.

LOCALIZER

SETUP 2211
DATE 6-7-63

Y DISTANCE-FT

300 200 100 0 -100 -200 -300 -400 -500

RUNWAY 0

5000 10,000 15,000 20,000

GLIDE SLOPE

SETUP 2211
DATE 6-7-63

ALTITUDE-FT

1000 500 0

ILS GLIDE SLOPE

TRAJECTORY

DISTANCE-FT

RUNWAY 0

5000 10,000 20,000
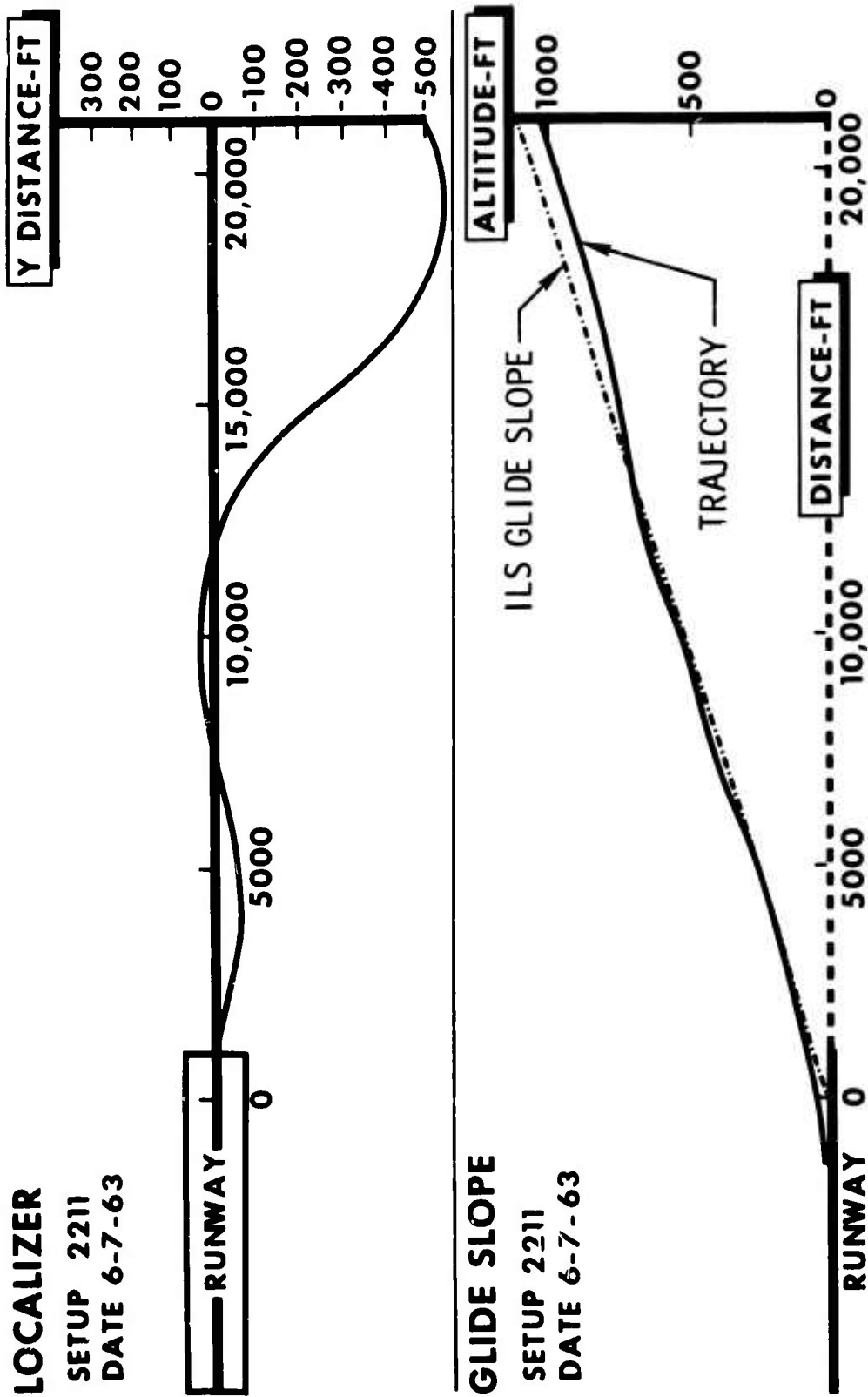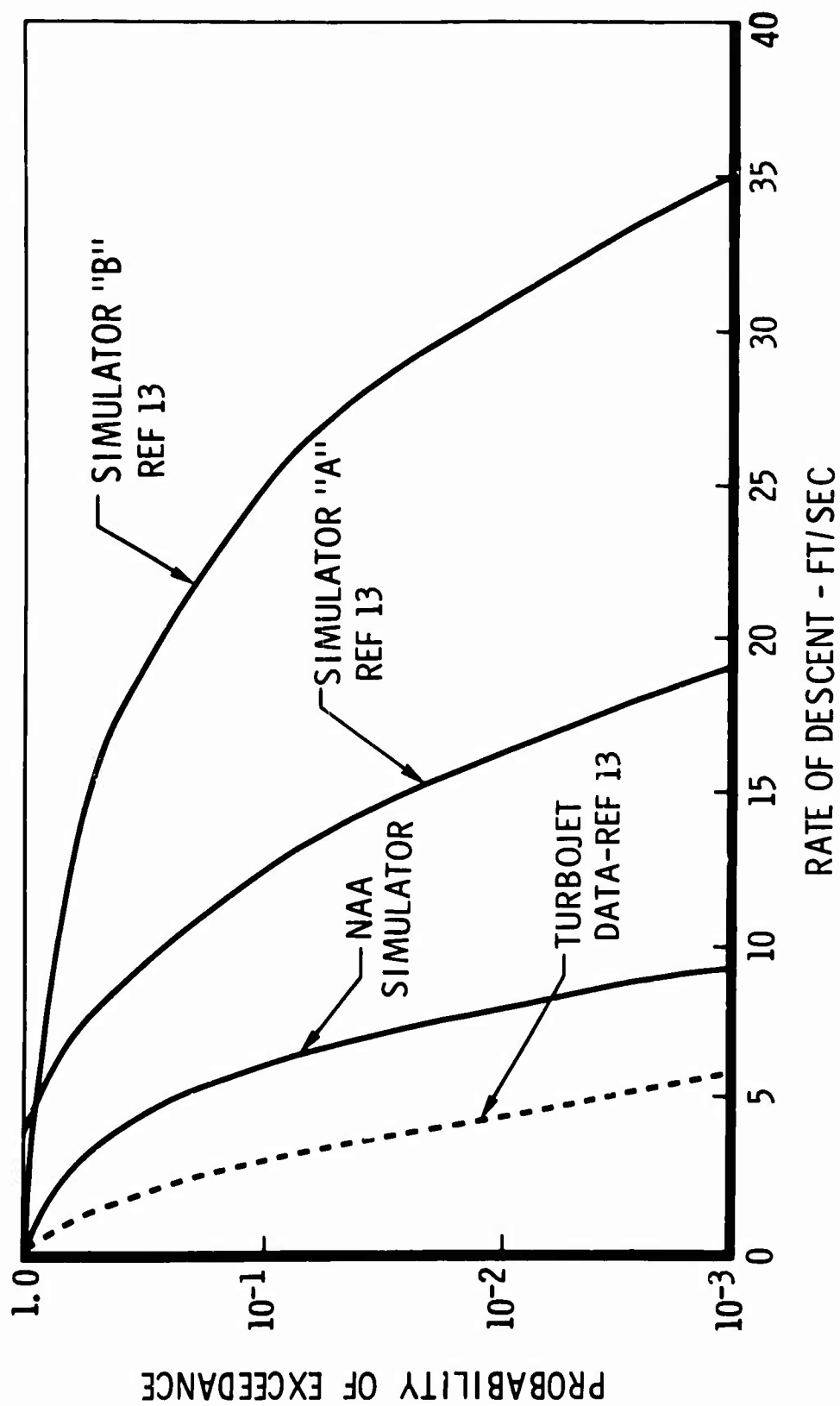
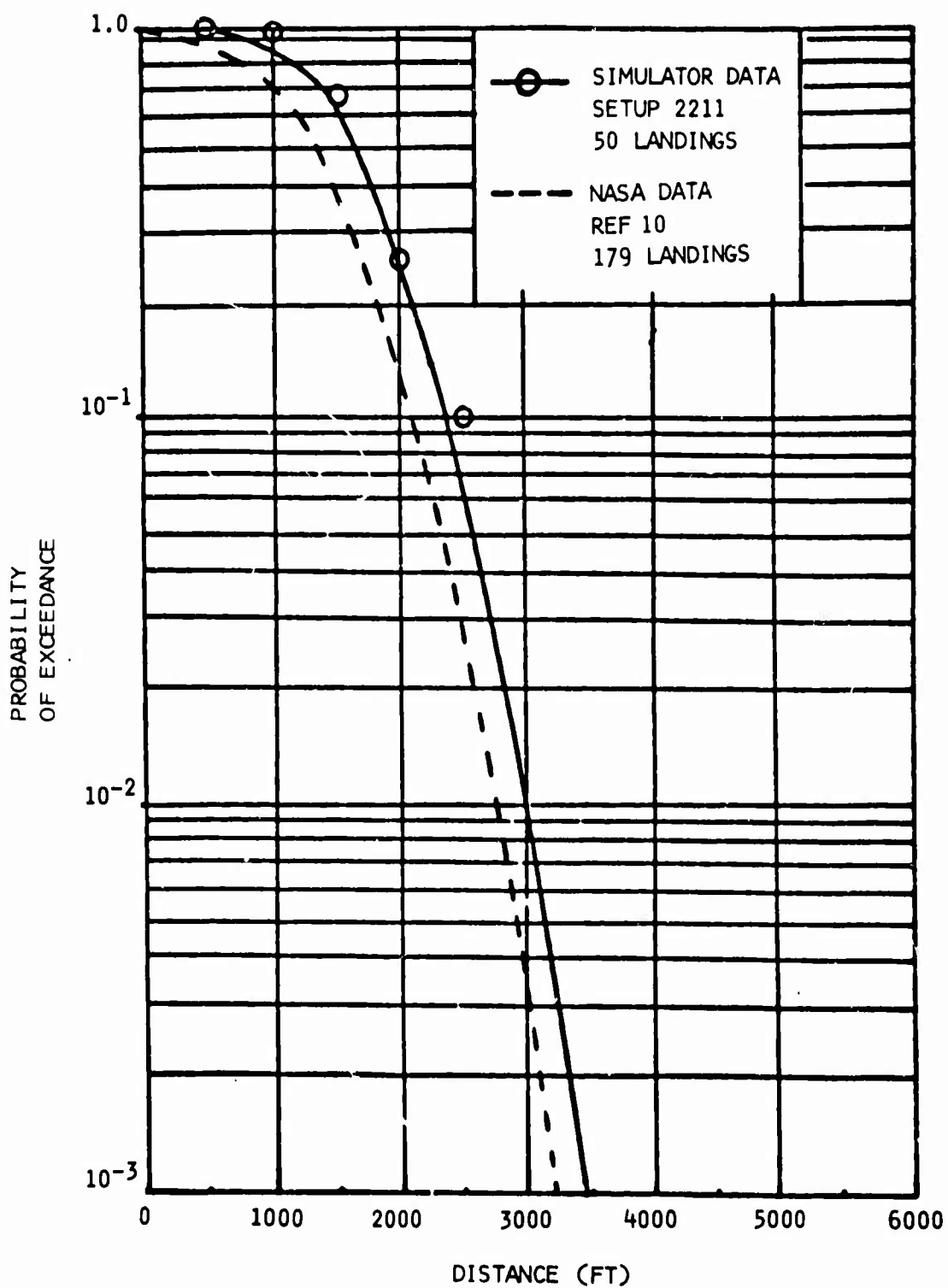Figure 16. Probability-of-Exceedance Curves - Vertical Velocity.

Figure 17. Probability-of-Exceedance Curve - Distance from Threshold.
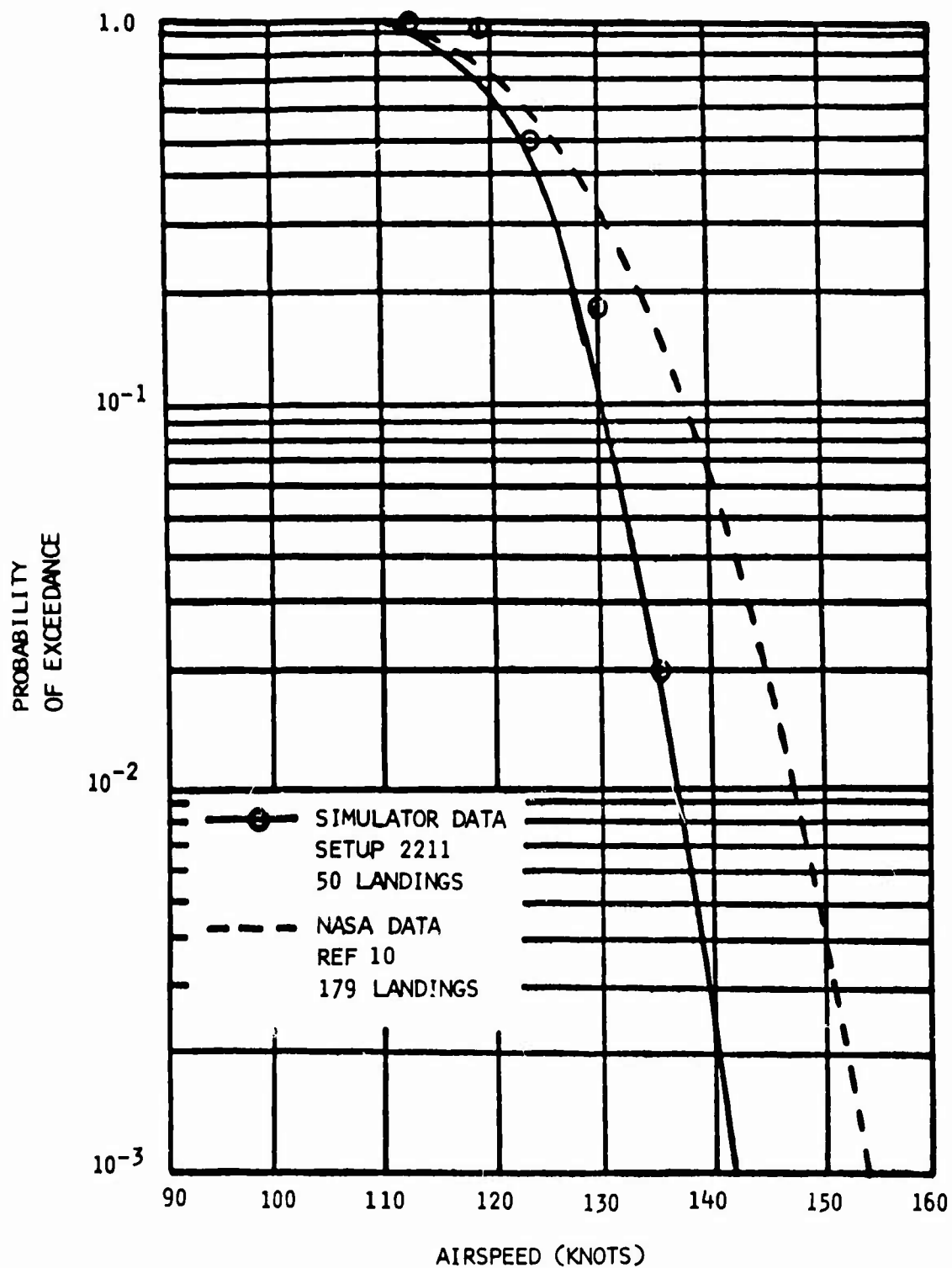
31

Figure 18. Probability-of-Exceedance Curve - Airspeed.

32
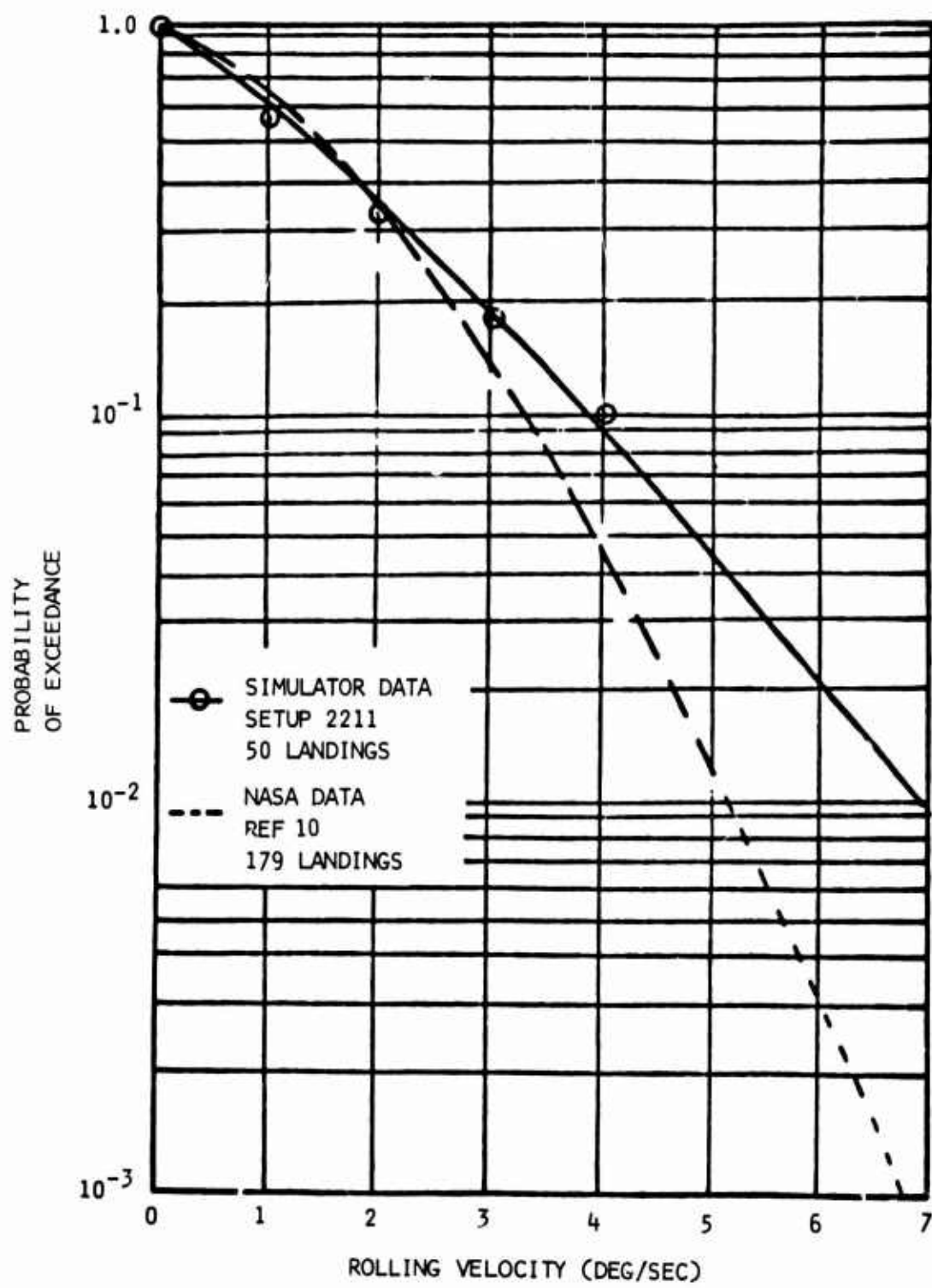
Figure 19.   Probability-of-Exceedance Curve - Rolling Velocity.
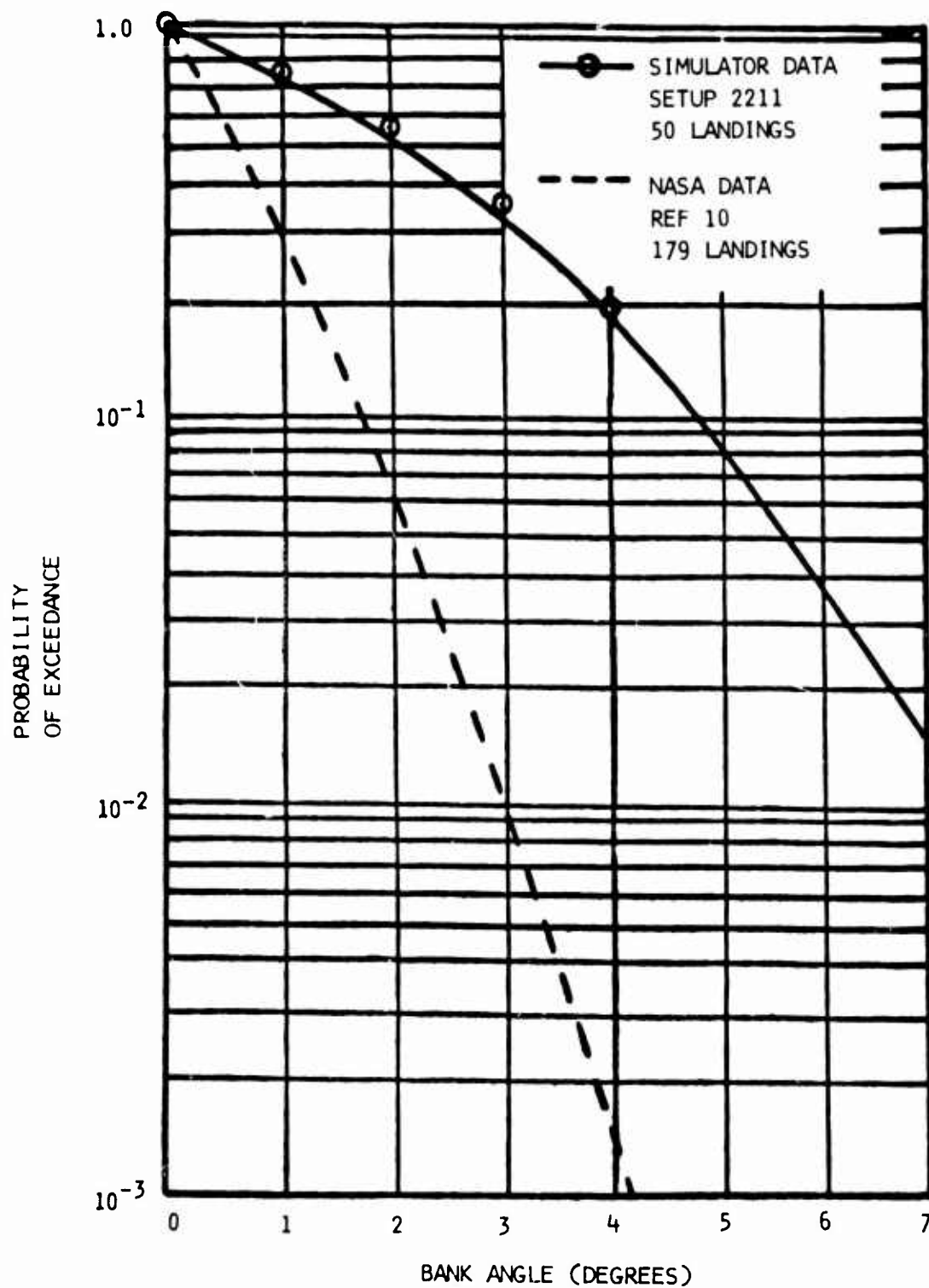
Figure 20. Probability-of-Exceedance Curve - Bank Angle.

TABLE III

STATISTICAL ANALYSIS OF SETUP 2211

PARAMETER	MEAN	RMS	THIRD MOMENT	FOURTH MOMENT	STANDARD DEVIATION	SKEWNESS	KURTOSIS
$\dot{X}$ FPS	0.18688 03	0.18722 03	0.65982 07	0.12461 10	0.11271 02	0.10054 01	-0.19857 01
$\dot{Z}_w$ FPS	0.42380 01	0.45380 01	0.10683 03	0.60460 03	0.15375 01	0.11659 01	-0.15364 01
X FT	0.17843 04	0.18400 04	0.67986 10	0.14364 14	0.44929 03	0.10913 01	-0.17469 01
P RAD/SEC	-0.21408-02	0.41880-01	-0.25941-04	0.11747-04	0.41825-01	0.35317 00	0.8188 00
Q RAD/SEC	0.87172-02	0.14859-01	0.44424-05	0.13055-06	0.12033-01	0.13541 01	-0.32208 00
R RAD/SEC	0.12182-02	0.11579-01	-0.49079-06	9.65988-07	0.11515-01	-0.31613 00	0.67079 00
ϕ RAD	0.18408-02	0.53922-01	0.17798-04	0.20439-04	0.53891-01	0.11352 00	-0.58236 00
θ RAD	0.40364-01	0.44749-01	0.10634-03	0.59948-05	0.19320-01	0.11867 01	-0.15050 01
ψ RAD	0.44604-02	0.37622-01	0.23451-04	0.54380-05	0.37333-01	0.44038 00	-0.28569 00
β RAD	-0.72290-02	0.21457-01	-0.72302-05	0.65391-06	0.20203-01	-0.73187 00	0.84851-01
V_T FPS	0.21142 03	0.21158 03	0.94928 07	0.20161 10	0.81520 01	0.10023 01	-0.19940 01

A sample trajectory of a typical simulator landing is given in Figure 15. The initial conditions at the outer marker were randomly selected. In this sample case, the airplane is 100 feet below the glide slope, 500 feet to the left of the localizer, and being blown to the left by a 10-knot quartering crosswind. The trajectory shows that the pilot homes in on the glide slope and the runway centerline. Although he was not apprised of the crosswind, he soon realizes it and flies it out.

Table III shows the seven statistical properties for the 11 state variables at the instant of touchdown, specifically requested by the customer of this landing simulation program. These statistics were computed from a sample of 50 simulator landings. The values are presented in standard floating point rotation, decimal fraction times a power of 10, the last two digits being the exponent. The mean, RMS, third moment, fourth moment, and standard deviation are statistical quantities which are more familiar to most than skewness and kurtosis. Skewness (more properly referred to as the coefficient of skewness) was computed from the following relation:

$$(\text{skewness}) \ \gamma_1 = \frac{\mu_3}{\mu_2 \ 3/2}$$

Kurtosis (also referred to as the coefficient of excess) was computed from the following relation:

$$(\text{kurtosis}) \ \gamma_2 = \frac{\mu_4}{\mu_2^2} - 3$$

Broadly speaking, skewness and kurtosis are indicators of how the probability distribution of the statistical sample are related to normal distribution. Skewness, as the name implies, is a measure of asymmetry. A negative value shows that the distribution is skewed to the left, and a positive value shows that it is skewed to the right. Kurtosis is a measure of the flatness of the curvature (hence also the peakedness) of the probability distribution curve. Since it is related to the fourth moment, a higher value of kurtosis indicates a flatter or broader peak, and a smaller value indicates a less flat top (or sharper peak).

Besides the tabulated statistics of the simulator data, many probability-of-exceedance curves using the Pearson type III distribution were also contractually required. A sampling of these curves are presented in Figures 16 through 20. The NAA simulator curves are of the Pearson type III family, generated from various parameters which were computed from the simulator data according to Pearson's formulae; whereas, the discrete points overplotted on the curves were obtained directly from the

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frequency distribution of the simulator data. Since the Pearson type III curve assumes a skewed distribution, absolute values were used in parameters such as bank angle and roll rate at touchdown. Probability of exceedance curves from flight data were extracted from References 10 and 13 and plotted on the same graphs as the corresponding simulator data for convenient reference. Although technical correlation analysis was beyond the scope of this program, cursory comparison of the probability curves with some comments from the simulation point of view may enhance the understanding of the simulation data.

The probability of exceedance of rate of descent at touchdown is presented in Figure 16. Much interest was shown in this parameter, because a major concern of the customer is the impact loads for landing gear specifications. It was shown in Reference 13 that both commercial simulators "A" and "B", used in "as is" condition, were inadequate for such R&D landing studies. Furthermore, some had raised the question as to whether VFR landing simulator studies are within the realm of simulation capabilities. The impression of those who were in touch with the NAA/LAD simulator landing study is also suggested on Figure 16; namely, that the NAA/LAD simulation represents a significant improvement over simulators "A" and "B" and that VFR landing simulation merits further consideration.

It should be stated here that data labeled "flight test" should not be categorically considered normative. There are confidence limits associated with flight data measurement, recording, and reduction.

The most similar comparison seems to be at the point of touchdown distance from the runway threshold. The ILS glide slope directs the airplane to a point 1000 feet from the threshold. With a flare, the normal landing should touch down at a point beyond the 1000-foot mark. The average simulator landing (Setup 2211) touched down at 1784 feet from the threshold (Table III), and the probability-of-exceedance curve (Figure 17) compares reasonably well with the reduced flight data. The simulator distance is approximately 250 feet greater than the flight data. This discrepancy may be due to visual display lag. Since the subject program was the first application of the visual display system, this lag had been overlooked. Hence, the internal inconsistency of the simulation between VFR and IFR would be approximately 250 feet. Accounting for the lag, the probability curves would show a very high degree of correlation.

The airspeed at touchdown (presented in Figure 18) shows that the simulator is landing slower than the airplane. The difference may be procedural, because the air carriers may well desire a higher-than-design

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landing speed. On the other hand, the lower airspeed may be induced by simulator inadequacies. For example, the relatively poor visibility of the display may affect the flare and the touchdown. In normal landing procedures, the throttles are already pulled back to idle at the flare, because the landing has been committed. Holding the airplane airborne longer, using more runway, and dissipating airspeed seem to be a probable explanation.

The results of rolling velocity and bank angle at touchdown (shown in Figures 19 and 20) point to a significant difference between airplane and simulator. It is more difficult to keep wings level on the simulator. The difference between simulator and real world is the horizon line of the visual display. Peripheral visual information is absent in the simulator, and the visual resolution of bank angle is not as precise as the real situation. Another factor which may influence the roll results is the predominance of crosswinds in the simulator landings. Two-thirds of the landings had crosswinds which can come from either side, whereas in an actual airport, there is a dominant pattern of wind conditions.

FS-001 HOVERBUGGY SIMULATION

The HoTran Simulator (shown in Figure ⁷ ⁷ was used for the simulation of the FS-001 Hoverbuggy. The cockpit was mounted on a moving base with three degrees of freedom: pitch, roll, and vertical travel. The range of useful travel and the rate limits are as follows.

Pitch: $\pm$8 degrees with 15 degrees per second
Roll: $\pm$40 degrees with 20 degrees per second
Heave: $\pm$6 inches with 10 inches per second

The six-degree-of-freedom nonlinear equations of motion are used to describe the Hoverbuggy dynamics. Due to the limitations of the Hoverbuggy, neither conversion nor high-speed flight is provided in the mechanization. The simulator cockpit was open as in the Hoverbuggy, and the simulator was flown with VFR, also as in the Hoverbuggy.

The HoTran Simulator has a variable-feel control system. Through hydraulics and control circuitry, all three axes of flight control can be adjusted to match the control system to be simulated. A wide range of adjustments can be made in the control system parameters, such as breakout, force gradient, friction, inertia, damping, and the location of the hard stops. In addition, various augmentation schemes were mechanized on the computers for control studies.
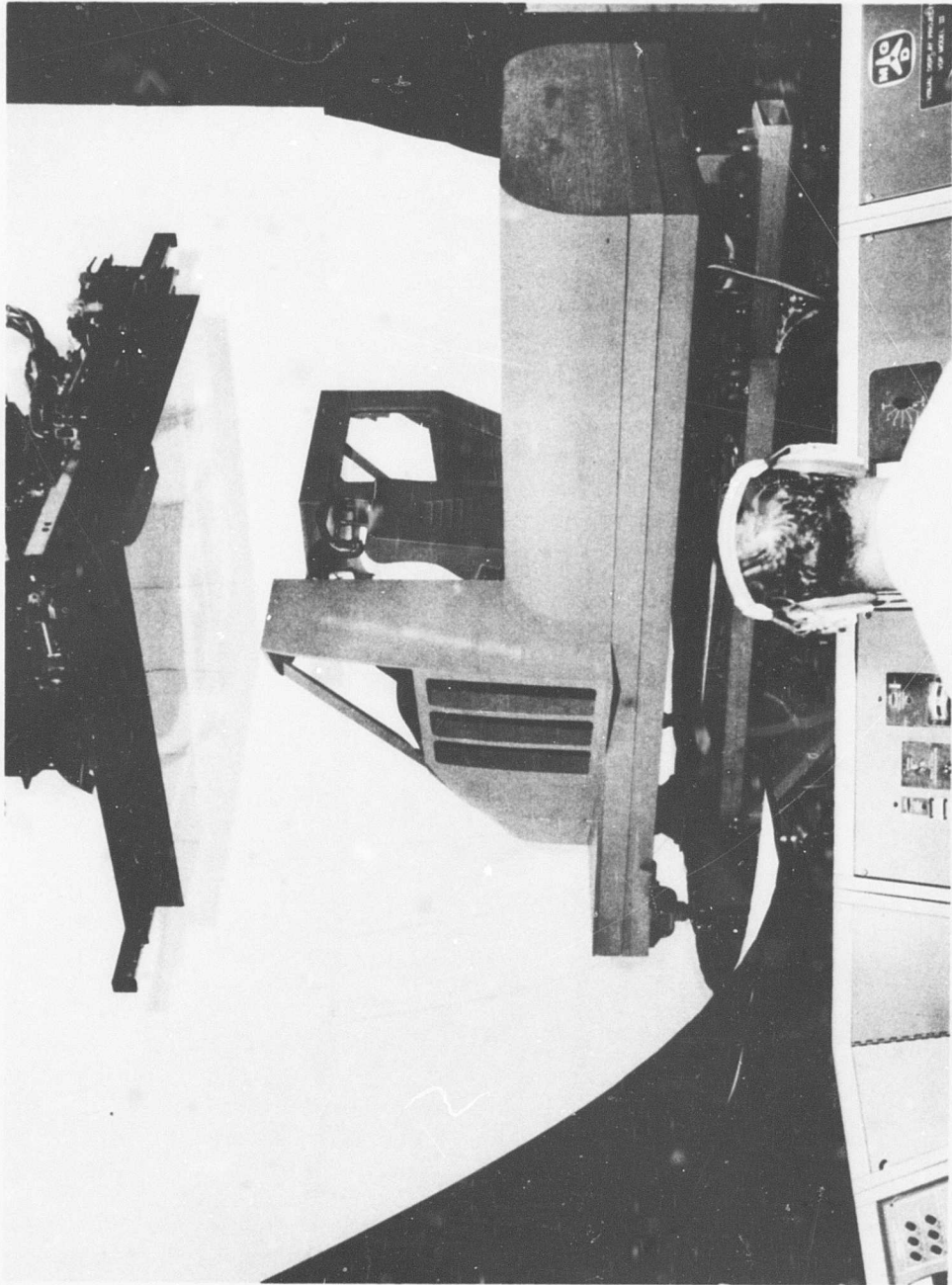
38

Figure 21. HoTran Simulator.

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In one program, reported in Reference 11, control sensitivity and damping were varied. Fifteen variations in each axis of control were flown, and data were obtained in the form of pilot opinion ratings, using the Cooper scale.

The comparisons of simulator and flight test are presented in Figures 22 through 24. The flight-test data are represented by the iso-opinion lines of rating of 3-1/2 (between satisfactory and unsatisfactory) and 5 (unacceptable). The simulator data are noted on the test points evaluated. Pilot A participated in both simulator and flight-test programs; the order of the tests was identical in flight and simulator, and the pilot was instructed to perform the simulator maneuvers in the same manner as in flight test. Since pilot A's experience in NAA VTOL simulation was limited, pilot B's data points are also included, in an attempt to indicate the effects of learning. Pilot B had not flown the Hoverbuggy, but he was an engineer with extensive experience in flying the VTOL simulator.

As shown in Figures 22 through 24, the comparison of simulator and flight-test ratings shows some good agreement for the satisfactory control configurations, but rather poor agreement for the unsatisfactory control situations with pilot A's data points. In these poor control situations, pilot A rated the Hoverbuggy better than the simulator, suggesting that he was more proficient with the actual hover craft than with the simulator. The simulator data of the proficient simulator pilot (B) correlate well with the flight-test data of the proficient flight-test pilot (A).

However, the discrepancies between simulator and flight-test ratings indicate some inadequacies of the simulator which seem to be accentuated in difficult control situations. In order to improve the simulation, pilots' comments concerning simulator deficiencies were investigated.

One dissimilarity between simulation and flight test was in the visual display. The course layout was not the same. One pilot commented that the visual cues of forward and lateral translational speed in the simulator tended to be higher than in flight. In response to this comment, a test was run, and the results are reported in Reference 12. Over-the-shoulder films taken during Hoverbuggy flights were analyzed to obtain some objective data for comparison with simulation. In the selected maneuver, the Hoverbuggy was initially in hover. Then a bank angle was established, causing the vehicle to translate for some distance. Then the bank angle was reversed, bringing the vehicle to a level-flight hover condition. The time history of the bank angle ex-
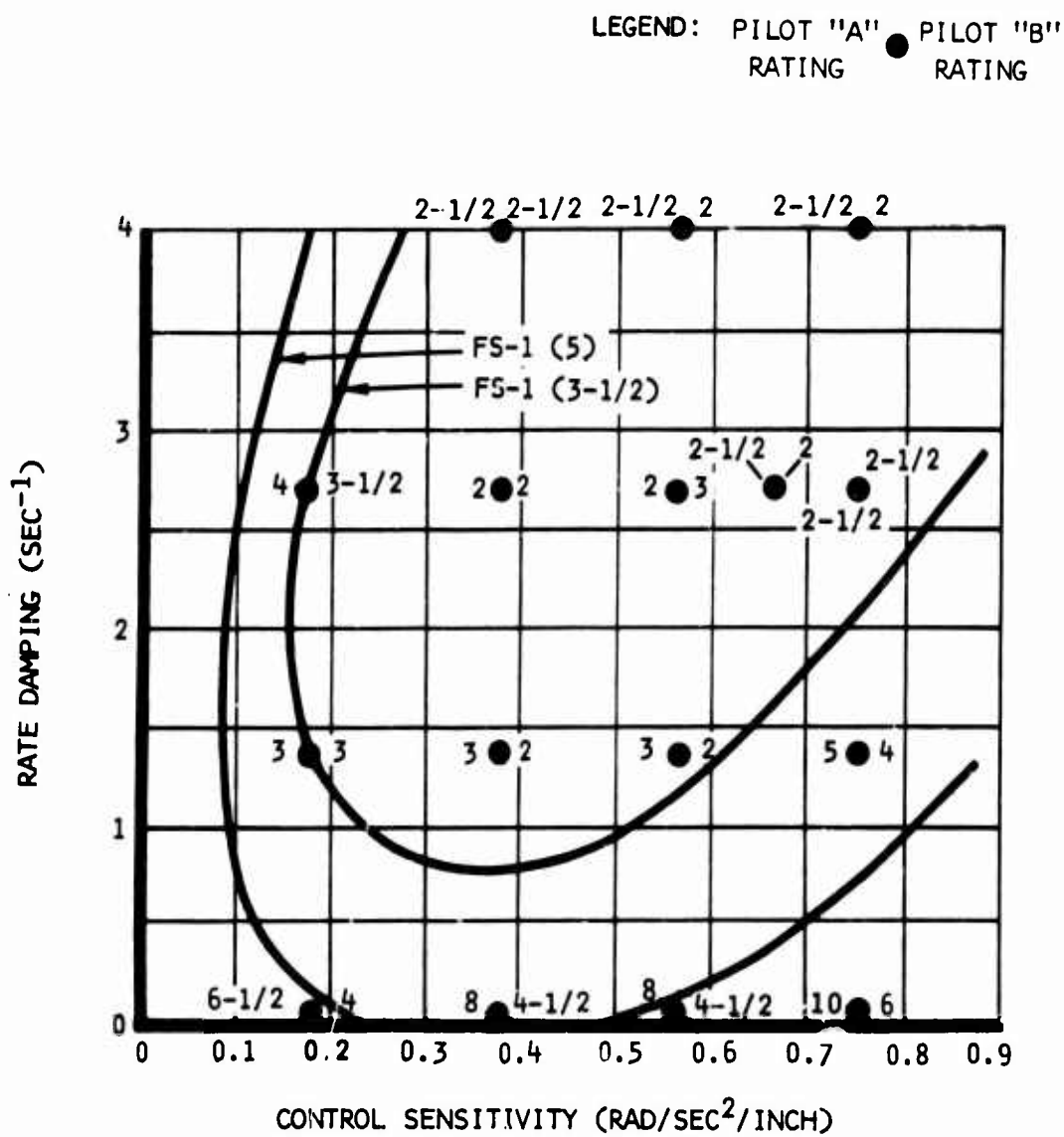
Figure 22. Pitch-Axis Data Correlation - Pilot Opinion Rating.

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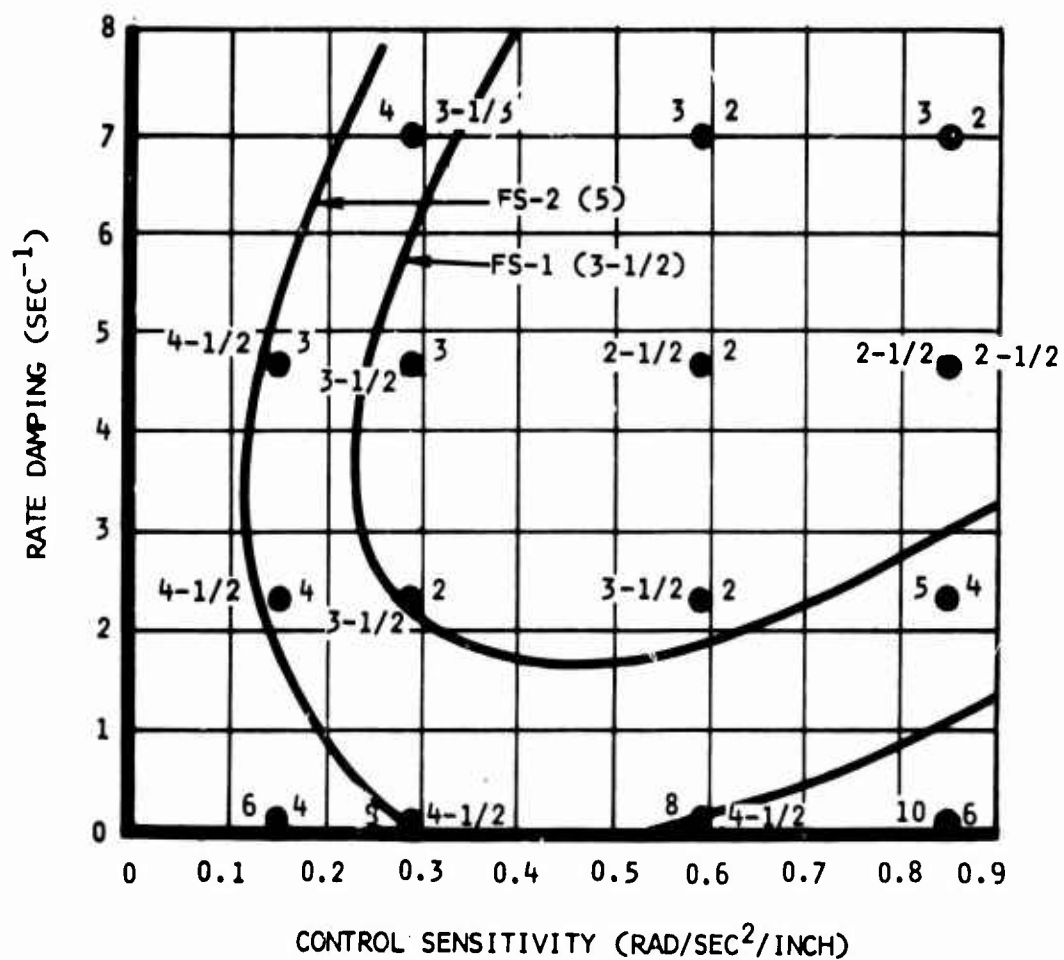
Figure 23.   Roll-Axis Data Correlation - Pilot Opinion Rating.

42
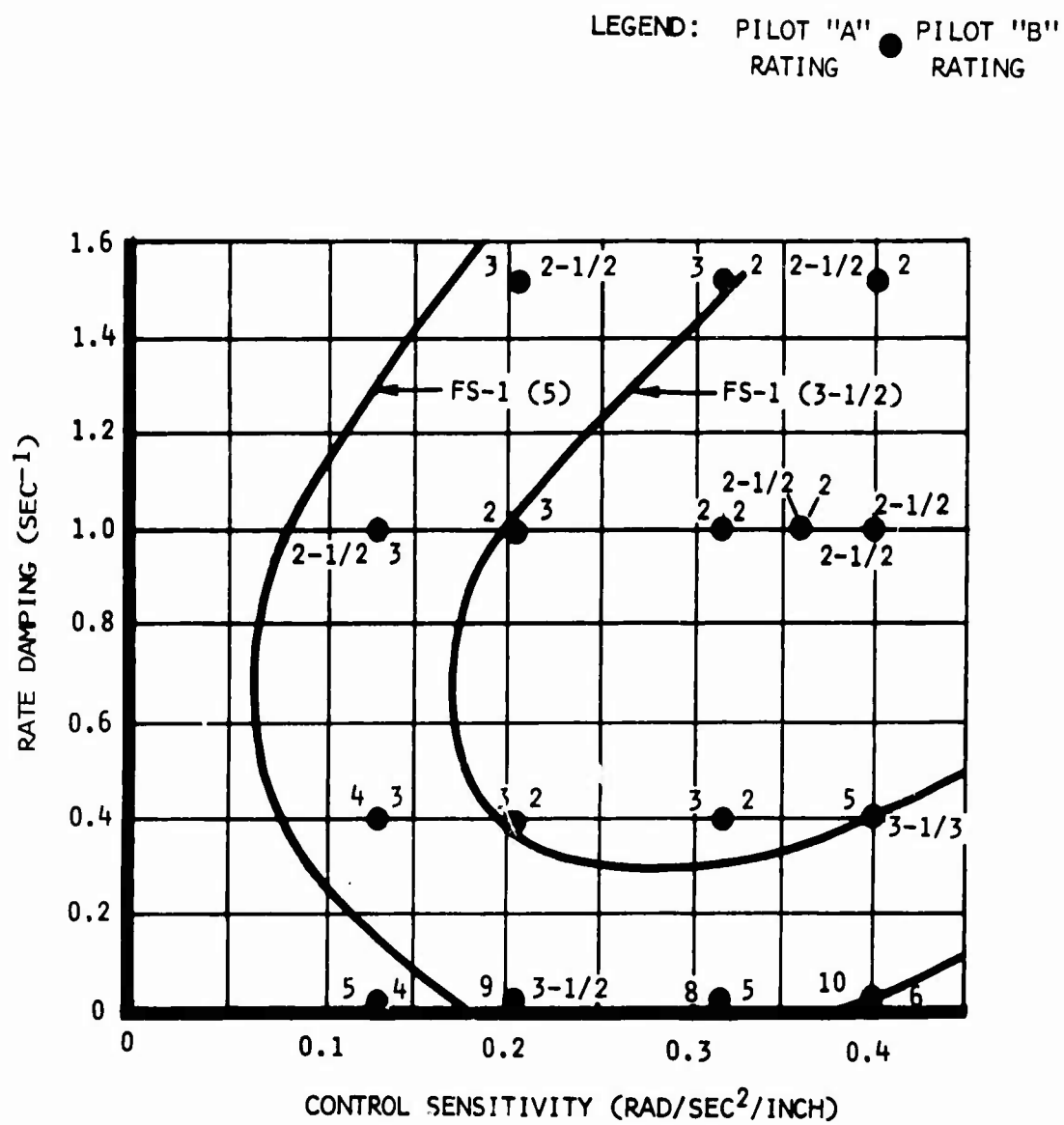
Figure 24.   Yaw-Axis Data Correlation - Pilot Opinion Rating.

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tracted from the flight film was used as the input to the computerized simulation. The resulting translation of the simulation compared very well with the translation extracted from flight test. This comparison, shown in Figure 25, tends to establish two things: (1) the estimated data used to represent the FS-001 are quite good, and (2) the computer translation and velocity are in agreement with flight test. However, this does not completely resolve all of the problems. Since visual displays with curved screens can at times introduce velocity distortion, other steps to determine the source of the apparent erroneous impression are being taken.
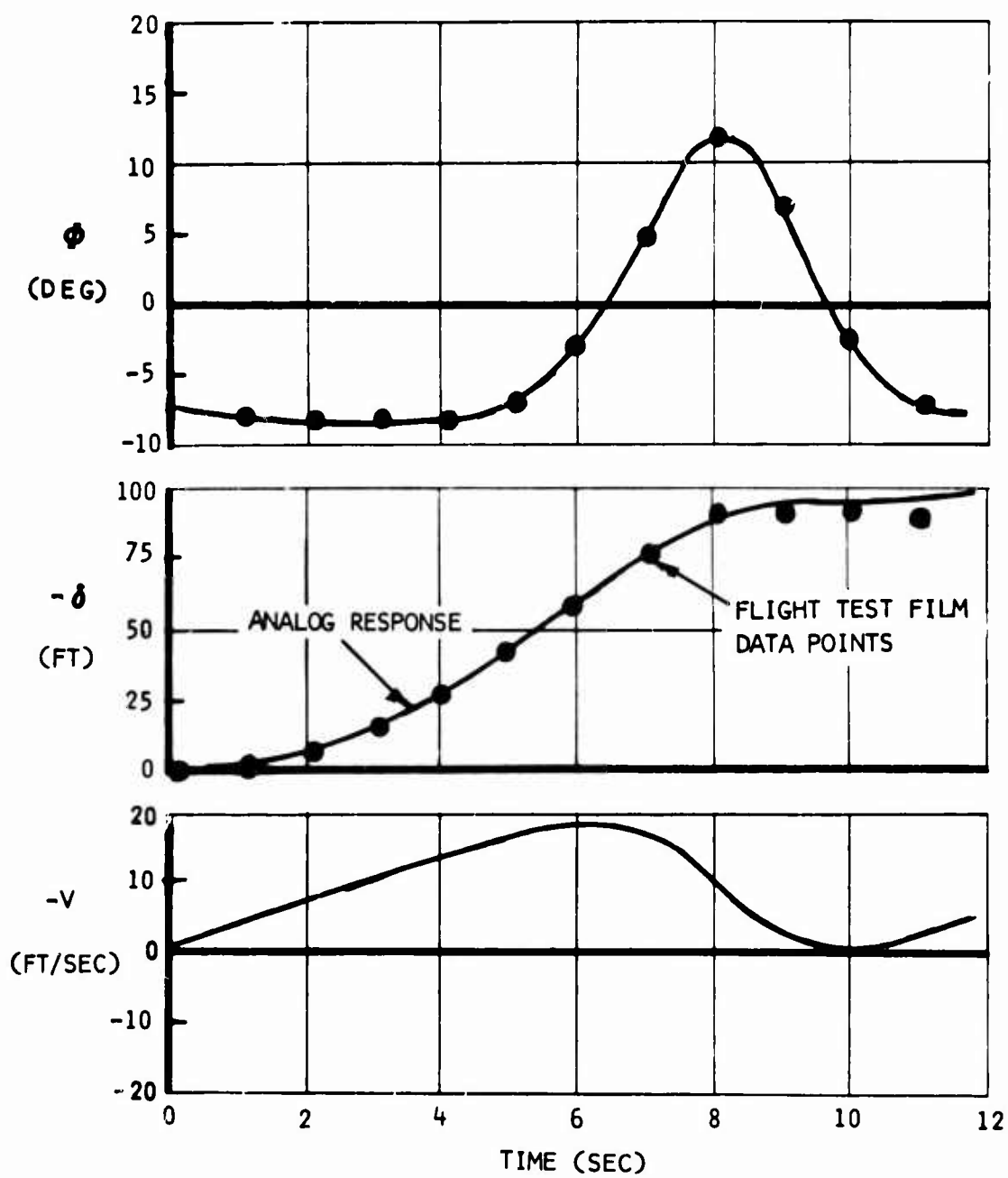
Figure 25.   FS-001 Flight Test Match.

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Section II

SIMULATION TECHNIQUE

However obvious, some of the overall, inherent limitations should be reiterated before embarking on a more detailed discussion.

"Ground-based" simulators, as the name implies, are attached to the ground, limited in the amplitude of cockpit motion, and lacking in many kinesthetic, visceral, and psychological aspects of aircraft maneuvers. Although they are potentially less dangerous and permit safer investigations of emergency conditions than do the aircraft themselves, they lack the same stress level in physical strain and mental anxiety. Even the most sophisticated "whole task" simulator is in actuality only a "multi-part-task" simulator which does not simulate the intricate airplane in its entirety. Simulation, as the word implies, proposes only to behave like the airplane in, hopefully, a strikingly similar fashion. The goal of simulation is to create a dynamic model of the aircraft with sufficiently similar characteristics and environment to evoke the same response from the human pilot.

Since each simulation is configured for a particular task (generally multipurpose), many decisions are made at its conception concerning the basic elements required and their levels of sophistication. Although the task orientation is primarily related to the program design and the associated maneuvers, there are other effects related to some seemingly subjective requirements of the pilot which engineers are apt to overlook. Objectively speaking, a human being can be requested to concentrate on a particular task; however, the pilot is trained not to ignore the total conditions of flight. Consequently, many peripheral items must necessarily be simulated in order to enable the pilot to concentrate on the program. The following is a brief discussion of the various building blocks to be considered for an integrated simulation complex. Although the most apparent implication is that each building block enhances the validity of the simulation, this is neither necessary nor sufficient. The major thrust of the critical discussion is intended to point out the importance of engineering integrity from many disciplines focused on the details of the entire simulation process.

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COMPUTERS

The utilization of computers does not guarantee accuracy and pre-
cision. Accuracy is related to sound theory in the "correct" representa-
tion of the system and/or subsystem, and precision is related to the
mechanization or programming of the computers to maintain the integrity
of the data. Some have argued that since the data are imprecise, the
computerization can be commensurately crude. Such error in thinking
widens the confidence limits unnecessarily. Furthermore, the consequences
become more dire if the laxity is extended to the dynamic representation
of the theoretically exact formulation of Newtonian mechanics.

The equations of motion used to describe the aircraft dynamic situa-
tion are derived from Newtonian mechanics, with a moving axes system de-
vised by Euler. The Eulerian axes are fixed to the aircraft rather than
the inertial reference frame. There are many variations of the moving
axes system referenced to the airframe, the two most widely used in air-
craft dynamics being stability axes and body axes. In the stability axes
system, the origin is fixed at the center of gravity of the aircraft,
with the longitudinal axis aligned with the projection of the relative
wind vector on the plane of symmetry. As the name suggests, the stability
axes system is especially useful in stability analyses about a steady
flight condition. The large majority of the dynamics simulation activi-
ties on the F-86, F-100, and F-107 were accomplished with stability axes
equations. The longitudinal and lateral-directional modes were uncoupled
and investigated separately. This approach was found to be adequate for
many applications in aerodynamic stability and control, control system
optimization, handling characteristics, and flying qualities.

As aircraft technology advances, the simulation program becomes more
sophisticated; more complex maneuvers are required; the continuous flight
regime to be simulated is expanded; and the dynamicists are favoring body
axes over stability axes. In the body axes system, the longitudinal axis
is aligned with a reference line on the aircraft body, regardless of the
direction of the relative wind.

In one variation prompted by mechanizational expediency, the force
equations are written in body axes which are referenced to the fuselage
reference line (FRL) - the basic reference of wind tunnel and other aero-
dynamic data. However, the moment equations are written in the principal
axes system in which the products of inertia vanish. To make the force
and moment equations compatible with each other, a transformation which
is a simple rotation in the x-z plane is required. In this innovation,

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the complicated mechanization of the product of inertia terms is replaced by a simple rotation. This is not to say that this is the best approach for all programs, but to show that there is room for engineering ingenuity in tailoring the computerization to fit the task.

To insure that the mechanization of the aircraft dynamics on computers is correctly programmed and that the integrity of the data is maintained, both static and dynamic checks are required. Theoretically, a comprehensive static check should be sufficient; however, in actual practice the dynamic checks have been most revealing. Dynamic checks such as transient and/or frequency responses have often led to a better understanding of the dynamic situation, the criticality of certain terms, and the idiosyncrasies of the particular simulation. Moreover, dynamic checks have uncovered some errors not revealed in the static checks; human nature is such that independent checks are often needed as safeguards against seemingly inconsequential mistakes. Because recent simulations are more complete and complex than the linearized mechanizations of the past, transient response checks have replaced frequency response checks. Since nonlinear systems are amplitude sensitive, comprehensive dynamic checks of the entire amplitude range are unduly cumbersome; the primary benefits can be obtained with spot checks of transient responses which are devised to exercise all the nonlinearities. On this basis, the analytical model has been validated in many comparisons of simulator and flight-test records.

In the foregoing static and dynamic checks, the electronic computerization of the simulator is checked against the mathematical solution of the analytical model. These checks are used to assure that the integrity of the data and the equations is maintained. The same type of dynamic checks can and have been used to compare the simulator with actual flight. Good agreement in these comparisons not only checks out the particular simulation, but also attests to the validity of the methodology. Hence, past correlation can give credence to future simulations, if the same principles of analytical mechanics are used to derive the equations, the same engineering methods are employed in the generation of the data, and the same integrity is used in the simulation. The dynamic checks have been discussed in the comparison data presented in Section I. Examples of the stability checks are given in Tables I and II, and transient matches are shown in Figures 6, 10, 11, 12, and 25.

In summary, the validity of the computerization of the aircraft is dependent upon the adequacy of the analytical description, the accuracy of the input data, and the proficiency in transforming the mathematical model into a computerized model.

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Although there is much room for error in the above process, many comparisons between simulation and flight test have been made which show a high degree of validity in simulation. This accomplishment has been made possible only through the cooperation and engineering integrity of many related disciplines.

COCKPIT

The level of sophistication built into the simulator cockpit is largely dependent upon human factors considerations. One consideration is the "face validity" of the cockpit - the extent to which the simulator appears like the actual aircraft. In most situations reviewed for this program, the interior and exterior mold lines of the simulator cockpits, the instruments and their arrangement on the panel, the control arrangement, and the visibility (e.g., over-the-nose vision) match those of their corresponding aircraft.

It has not been established that "face validity" in every respect is required. Although some quantitative measure of merit may be expensive to obtain, it can be intuitively seen that "face validity" definitely benefits the closed-loop operation in suggesting to the pilot that he is in an actual airplane.

There are other important requirements on the instrumentation because of the large amount of IFR activity in simulators. A major consideration is the operation of the primary and secondary instruments necessary for the prescribed piloting task: the static and dynamic response, the hysteresis, the resolution, and other idiosyncracies such as smooth action, sticky action, or some characteristic jitter. Analytical descriptions of the in-flight characteristics are not readily available. In some cases, it is even difficult to obtain a description of the theoretical operation without looking into the hardware. In most simulations, only the important primary instruments are simulated in detail. Many other instruments are calibrated to give the theoretically correct value. Agreement with flight in such instances is dependent upon pilots' comments. Objectional differences between simulator and flight instruments are pointed out, and the simulation engineer is called upon to generate a more similar behavior of the instrument. Conversely, if the pilots do not complain, one can infer that the instrument is sufficiently correct. By this rather nonscientific but austere approach, some measure of correlation with flight is obtained during the checkout phase of the simulator development. Subsequently, a routine can be set up for daily checkout procedures to assure proper and consistent operation of the instruments.

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Although human factor considerations are often associated with cockpit arrangement, there are many other important human factors in the program design such as the intangible differences between simulator and flight programs and how they affect the results. A few such considerations are the workload, the radio communication checkpoints, and other burdens in following an actual flight plan. The pilot is generally busier in actual flight than in simulated flight; more demands are made on the pilot's concentration. In simulator programs, the workload of the real world and its effects on the pilot's performance are often ignored. For the sake of program efficiency, the simulated maneuvers are isolated from their historical context. Hence, their validity is dependent on the cooperation of the pilot, who is tacitly required to bridge the gap between the simulator and the actual aircraft in order to make up for the limitations of the simulator and the test program.

CONTROL SYSTEM

The controls represent the interface between the pilot and the aircraft. In a general sense, the controls include not only the flight controls but also the throttles and other switches, buttons, cranks, and levers which affect the aircraft and its systems. Of primary importance to the handling characteristics of the aircraft is the flight control system, which has to be tailored to fit the wide range of dynamic situations throughout the flight envelope. The control system can and often does make the difference between good and poor handling characteristics.

There are two types of information which the pilot senses from the controlling task. First is the "control feel," which is governed by the control hardware design with such characteristics as force gradient, breakout, friction, inertia, bobweight effects, rate limits, and damping of the system. The other information is the resultant aircraft response, which comes from the control gearing to control surface deflection to aircraft dynamics which are sensed by the pilot from the instrument, the motion feel, and visual cues. The adequacy of the control situation is governed by how precisely the pilot can relate the dynamic response with his control inputs.

From the analysis of data available from extensive flight-test programs of the F-86 and F-100 airplanes, some design criteria were determined for handling characteristic evaluations and nonlinear gearing specifications. Relationships between "control feel" and aircraft

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response were empirically formulated to address control problems such as sensitivity, overcontrol, pilot-induced oscillations, and rubber stick.

On the F-107 airplane, these criteria were applied, and the design and development of the control system were accomplished with the aid of the simulator.

The success of the simulator program and adequate correlation with flight may be inferred from the results. Although there were some hardware problems, the basic control concept developed on the simulator was sound, implying at least adequate correlation with flight.

Because of the importance of "control feel," much attention is given to duplicating the control system characteristics on the simulator. This has been accomplished in two different ways: (1) with an operational mockup of the flight control system, and (2) with a "variable feel" control system in general-purpose simulators.

There is an operational mockup of the flight control system associated with NAA/LAD-built airplanes such as the F-100, F-107, X-15, and XB-70. (See Figures 1, 4, and 5.) Actual hardware (linkages, bungees, hydraulic valves, actuators, etc) is configured as in the actual airplane. The advantages of such a system are obvious; the force feel, friction, hysteresis, inertia, damping, and other nonlinear characteristics are inherent in an operational mockup. However, there are also some disadvantages involved. The cost of an operational flight control system is prohibitive for simulation alone; simulation only reaps the benefits, because its existence is required by other functions in the hardware development. Being bolted to the ground, the above-mentioned system is unlike the airplane, because it is stationary and unaffected by structural deformation. There are no "g" loads on the components, although bobweight effects can and have been simulated in conjunction with the mockup of the flight control system.

The hookup of all the components, the checkout, and the calibration procedures are developed on the mockup. Hence, it may be said that the actual airplane system is like the mockup.

For general-purpose simulators such as the HoTran and the transport simulator, a variable-feel control system is employed. The system is essentially three force servos, one for each axis of control. It is designed for convenient adjustment of the control feel characteristics, such as force gradient, breakout, friction, damping, inertia, and the location of the hard stops. Such a system can be used to simulate

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practically any conventional control system, and it is very convenient for control system optimization programs.

The disadvantages are those of any hydroelectromechanical servo system. There are gain and frequency limitations and some inherent lags. Versatile systems are prone to human error and require some vigilance in obtaining and maintaining the desired characteristics.

MOTION SYSTEM

One of the most difficult tasks of ground-based simulation is to provide the pilot with the in-flight kinesthetic feel. For a simulator which is fixed to the ground, there cannot be a one-to-one relationship except in a special case such as small perturbations about hover flight. Limited travel is a severe limitation which presents problems in any motion scheme. The motion scheme used to drive the motion system is directed toward producing some of the motion cues that the pilot would normally feel during flight. Due to the limited travel, false cues are inevitably generated along with the desired effect. Some false cues may be so objectionable that additional false motions (such as washout, etc) are generated for compensatory purposes. In general, the goal of the motion scheme is to maximize the proper in-flight motion cues and to minimize the false cues. Thus, motion schemes are forced into a high level of sophistication - in thought and ingenuity, if not in actual implementation.

Because of the formidableness of the motion task (and the associated costs), many simulator programs have been conducted without any motion, with some degree of merit.

Simulation studies on the X-15 were conducted both on a static simulator and on a centrifuge. The significance of the comparative studies is that the centrifuge program did not invalidate the fixed-based simulator program and, furthermore, that the results of the controlling task are similar. One can infer that there is some merit in fixed-based simulation. However, one cannot conclude that motion is unnecessary in all cases.

There is some evidence which points to the need for motion. During the first glide flight of the X-15 airplane, a PIO condition was encountered in the landing flareout. Although this condition was duplicated on the simulator after the fact, it was not predicted. Although it was not established in this case whether motion played a significant part, other studies have indicated that the physical attitude of the cockpit and its variations offer important cues for landings.

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Another comparison occurred during the XB-70 program. Initial encounter with the landing characteristics of the fixed-based simulator seemed unreasonable. Hence, a brief study of the XB-70 landing characteristics was made on the moving-base transport cockpit, and in that sense more like the actual airplane. (However, subsequent landings on the XB-70 simulator were improved.) It was difficult to draw rigid conclusions from this comparison, because many parameters were beyond our control. It was not a clear case of motion versus no motion, because the cockpit, the instruments, and the control system of the transport cockpit were those of another concurrent program and not those of the XB-70, even though the characteristic responses were those of the XB-70.

Although no specific program had been conducted to compare motion with no motion, some informal observations were made on the transport cockpit during extracurricular activities of the 707 program. When the motion system was turned off, the control inputs were blatantly larger than normal, which is highly suggestive of the absence of associated motion discomfort. Pilots familiar with the 707 almost invariably exceed the limits of the airplane, seemingly on purpose. It may be said that cockpit motion associated with control input invites pilot cooperation in flying the simulator like an airplane.

In landing studies, a motion system is almost a necessity, because the primary indicator of touchdown is through motion: the pilot feels the jolt. Although there can be many other indications of touchdown, they lack the distinctiveness and face validity of the jolt.

Since the NAA/LAD approach to simulation is task oriented, the motion schemes used have varied from one program to another. The choice of motion schemes depends largely on the capabilities of the motion system and the piloting maneuvers to be performed. Although there are many variations of the same motion scheme, basically the following is used on the two-degree-of-freedom transport cockpit. The pitch motion is driven by essentially a pitch attitude signal, and the roll motion by a signal roughly equivalent to wash-out roll. It should not be overlooked that this scheme is a compromise; for example, it is erroneous for rudder kicks and engine-out conditions. On the HoTran cockpit, the pitch and the roll motions are driven by essentially a washed-out attitude signal, and the vertical travel is driven by a signal roughly equivalent to washed-out altitude. Of course, each signal is tailored to overcome the problems of that specific axis of motion and its associated limitations. If the desired effect can be clearly defined, then some ingenuity can be exercised in applying control techniques. One should not overlook the fact that many signals are available from

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the computer model of the dynamic situation. The selection of the basic signal or signals can greatly simplify the shaping or compensation task.

VISUAL DISPLAY SYSTEM

Some of the most significant advances in the state-of-the-art of simulation have been made in the area of visual display systems which give a pictorial representation highly suggestive of the real world. These visual display systems have greatly enhanced the realism of simulation and have extended the capabilities of simulators to include practically all types of flying conditions. In many applications, the increase of realism due to visual displays has been sufficient to overcome some hypothetical threshold of basic realism and enables the pilot to transfer simulator flying into aircraft flying. In general, the two basic features of realism are these: (1) the display is servoed in all six degrees of freedom to allow the pilot complete freedom to command the aircraft as in the real world; (2) the pictorial representation looks like the real world, which contains features such as sky, horizon, terrain, ground texture, and some cultural objects. Two such systems have been used at NAA/LAD: the MGD display on the HoTran Simulator used primarily for V/STOL studies, and the Link display on the transport simulator used primarily for conventional takeoff, landing, and low-altitude handling characteristics studies.

The realism which the visual display system contributes to simulation has prompted many favorable, unsolicited comments. For example, one airline pilot who participated in the 707 program wrote a letter of appreciation which included the comment that the simulation program had improved his landings on the actual airplane. If he made a rough landing on his regular run, he was not afforded another landing opportunity for many hours. However, on the simulator he could correct his mistakes in subsequent landings which were only a few minutes apart. A similar verbal comment was made by a check pilot who returned to a regular run during his participation in the program. He stated that the simulator program helped him to "sharpen up" his landings on the actual airplane.

In some simulation programs, the requirement for a visual display of the outside world is quite obvious; for example, takeoff and landing studies under VFR conditions. In other cases, the requirement is not so obvious; for example, in some control situations where IFR and VFR simulations evoke different pilot responses and different techniques in accomplishing the task. In a simulation study, various types of displays were used in the control evaluation study of a V/STOL aircraft. Both pitch and roll axis control were evaluated on an instrument-only display,

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a contact analog grid display, and a closed-circuit TV display of a terrain model. It was observed that much steeper attitudes develop under IFR conditions than under VFR conditions. Steep attitude indications on the ADI and on the contact analog were not as threatening as the confrontation with terrain. It was also observed that with instruments and contact analog, there was a greater tendency to "fly the simulator"; whereas with a pictorial display, there seemed to be a more realistic sensation of flying an aircraft. In the transport landing situation, the motion seemed to be more dominant in deterring unrealistic maneuvers on the simulator; the visual display seemed more dominant in the V/STOL situation.

Given the basic degree of realism, present display systems still leave much to be desired. Some comments gleaned from our experience with two systems should be made concerning the present limitations. In the area of realism, the low light levels of the display are incongruous with real life. Although the pictorial representation suggests broad daylight, the darkened cockpit and lighted instruments suggest night flying. The wide angle (200 degrees) of the MGD display includes much peripheral vision; however, this is not true of the Link display, which is limited to the front windshield. Besides degradation in realism, the visual resolution of roll attitude also suffers from the small vision angle (60 degrees). The map size also imposes some limitations on the program. The size of the transparency of the MGD display coupled with minimum altitude capabilities forces the segmentation of V/STOL programs into the three phases of hover, transition, and up-and-away flight; whereas the Link display permits all three phases in the same run. An inherent limitation of both Link and MGD systems is what may be termed parallax errors. Because the object image is focused on the screen at a relatively small, finite distance from the pilot's eyes, parallax errors occur with head movement. Current activity in advancing the state-of-the-art is dealing with this problem. Virtual image displays with large exit pupils, which are focused at infinity, are being developed. In such displays, when the head is moved from side to side, the "world" does not move.

Another problem in TV visual displays arises from the fact that TV camera focus cannot be servoed by the pilot's eyes. In the real situation, the pilot can select his point of focus which may or may not correspond with the optical situation being simulated by the TV camera. In normal operation, the camera is focused such that its depth of field covers the area which is anticipated to be of greatest interest to the pilot. However, in instances when the pilot is looking at an area outside the camera's depth of field, he cannot bring the image into focus with his eyes.

From a user's standpoint, smoothness of operation is paramount. Jerkiness has a way of destroying the sensation of realism, much more so than response lags or technically incorrect perspectives. In servo gain adjustments where trade-offs may occur, smoothness of movement should not be sacrificed for a faster response. Also, dead bands or other abrupt nonlinearities have been found to be more annoying than response lags and, consequently, should merit more consideration in compensation.

The same emphasis applicable to every building block of simulation is reiterated here with regard to the visual display system; i.e., the engineering integrity of the user-operator of the system. Over and above the effort in maintaining proper calibration and operation of the visual display system, someone should understand the role that the system plays in the integrated simulation complex to assure its performance in the closed-loop situation.

THE HUMAN PILOT

Assuming that the various building blocks are correctly interfaced and integrated, the correlation between simulator and airplane of each block does not guarantee correlation of the total integrated simulator complex. The fact remains that the simulator is still not the airplane. The total impact of all the differences on the piloting function must be considered.

In a sense, the human pilot constitutes another building block in the control situation. Although much analytical work has been done in simulating the human pilot, most analyses are highly simplified in comparison with the complexity of the actual situation. For example, in some recently developed analytical analyses, pilot opinion can be predicted for an airplane pitch control situation. One can determine analytically what is required of the pilot in order to accomplish the task: how quick must his response be, what is the frequency band of his inputs, and what amplitudes and what leads or lags must he mentally compute in order to compensate for the given control situation. However sophisticated these recent developments, the usual simplification is still one mode of pilot input (pitch control) carried through one loop to one aspect of dynamic response (pitch attitude); whereas in the piloting function, the actual tasks require multiple inputs through various loops, sensed by the pilot in many ways. The complexity, versatility, adaptability, and also inconsistencies of the human being have continued to defy analytical description.

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The importance of the pilot's role in simulation programs is usually given implicit intellectual assent, but the real significance of his role is often overlooked. The pilot is no ordinary human being; he belongs to a specially skilled and highly trained class. Embodied within him are the knowledge and experience of piloting airplanes. On one hand he can be annoyed by the differences between simulator and aircraft which block him from normal piloting technique, but on the other hand he can transcend some seemingly gross inadequacies of simulators. For example, many high "g" maneuvers have been conducted on static simulators with rather amazing success. With the X-15 airplane, the mission planning for the flight-test program was accomplished on the simulator. The flight profile predicted on the simulator compares quite closely with the actual flight. (See Figures 7 and 8.) As previously mentioned in the motion discussion, the centrifuge program showed that the "g" loads did not materially affect the pilot's performance as compared with the static simulator. Here, the comparison with flight indicates a similar conclusion. One particular coincidence which occurred during the X-15 flight-test program showed rather dramatically the success of the X-15 simulation. This incident was reported in Reference 7 as follows: "We are thankful that we have but one flight in which simulator preparation for this type of emergency was actually put to use. On this flight, an intentional throttle reduction resulted in a premature engine shutdown. Simulator training flown by the pilot shortly before the flight had shown that Rogers Dry Lake at Edwards could not be reached from that point in the trajectory; however, Cuddeback Lake, which is approximately 20 miles northeast of Edwards, could be reached. The decision was made immediately and without hesitation to change course and land at Cuddeback. The landing was accomplished without incident and the altitude and speed over the lake at the beginning of the landing pattern were very close to the values predicted on the simulator. This incident indicates the high degree of confidence placed in the simulator by the X-15 pilots."

Another coincidence occurred during the ZEL program. An emergency condition investigated on the simulator developed during the second launch when the rocket booster did not separate after burnout. With the empty booster case attached at the aft end of the F-100, the aircraft is statically unstable. However, during the simulator study this unstable condition was controllable, and the pilot was able to transfer his learning on the static simulator to the actual dynamic situation of flight.

The foregoing examples of the X-15 and the F-100 ZEL program indicate that the human pilot can overcome some of the most severe limitations of simulation. A high degree of transference has been obtained from a stationary simulator to high g-load flight. On the other hand,

however, there have been examples in which seemingly inconsequential items have blocked the participating pilot from flying the simulator like an airplane. On the transport simulation reported in Reference 9, many items which are rather tenuously associated with the piloting task are included to induce pilot cooperation. Although this simulation has been considered the most realistic of the NAA/LAD simulations, some pilots who are intimately familiar with the airplane have demonstrated that minute differences can be extremely annoying.

Hence, the value of pilots' cooperation cannot be ignored. The program design, the briefing of the pilot before the program, his understanding of the program tasks, and his role in arriving at the objectives have been found to be of utmost importance to a successful simulation program.

The degree of validity of the entire simulation complex in piloted maneuvers has been shown in the data presented in Section I. Comparison of simulator with flight test at the pilot opinion level is given in Figures 13, 22, 23, and 24. Samples of overall mission performance are shown in Figures 7 and 8, and performance on the statistical level is given in Figures 16 through 20. The degree of merit in past simulations cannot be attributed to any one item, but to the entire simulation process with some highlights in each of the building blocks previously discussed.

Section III

CONCLUDING REMARKS

In the review of past NAA/LAD simulations for the subject program, it can be seen that the entire simulation process is directed toward accurately producing those aircraft characteristics which are germane to the problem of aircraft design and development. Some of the general features which may be significant in producing successful simulation are summarized herein.

A major emphasis is placed on the computer program, because it is the analytical model which embodies the aircraft characteristics on which the flying qualities and handling characteristics depend. The three important aspects of the computer program are the selection of the proper equations, the accurate representation of the data, and the adequacy of the method of verification.

The equations of motion are tailored for the specific task. There can be many consistent sets of equations derived from the same principles of analytical mechanics. However, some equations are more suitable for effective programming than others. In a typical six-degree-of-freedom program, body axes force equations are coupled with principal axes moment equations through a rotational transformation. The cumbersome product of inertia terms which generally appear in the moment equations have vanished by virtue of the principal axes. In its stead, a relatively simple rotational transformation appears.

The validity of the simulation is dependent upon the given data. Simulation precision is applied to all data, regardless of the confidence limits of the data. The simulation should rise and fall with the accuracy of the data, but not with simulation carelessness. Heavy emphasis is placed on the nonlinearities, because they often produce the distinguishing characteristics of the specific aircraft simulated.

The computer programs are thoroughly checked and verified in great detail. Static checks which check all the loops and branches of the mechanization are necessary but are not sufficient. Dynamic checks which excite all the modes with sufficient amplitude to exercise the nonlinearities are required for verification of proper simulation of the dynamic characteristics.

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Experience with the closed-circuit TV visual display system has shown that the most important check is made at the final output, the picture that is presented to the pilot. Daily checks are made not only for calibration of amplitudes but also for the perspective and orthogonality of the TV signal (horizontal and vertical linearity).

The motion requirements of a ground-based simulator are not a one-to-one correspondence with actual flight. Pilots are more particular about the direction and timing of the motion cues than they are about the amplitude. Hence, phasing is considered to be dominant over the magnitude.

The force feel of the control system is considered to be a key link in pilot acceptance. In the aircraft control situation, the pilot must relate the aircraft response with his inputs, and he senses his inputs through the force feel of the control system, which includes the breakout force, the friction level, the force gradient, the inertia and damping of the system, and the gearing (or control power).

Finally, it 'ould be stated that the successful simulation programs have been the product of team effort - from the personnel who generate the data, produce the simulation, and check out the hardware to the pilot who fills in all the other subjective aspects which have defied analytical description.

REFERENCES

1. IOL FSL 59-1-11, "Additional Details for Renegotiation Writeup"

2. NA-54-1397, "Preliminary Analysis of the Response of the F-100A in Abrupt Aileron Rolls - Reeves Electronic Analog Computer Study"

3. NA-58-1685, "The Analog Phase of an F-100D Zero Length Launch Simulation"

4. NA-57-547, "Phase I Flight Test Report F-107A No. 1, AF55-5118"

5. IOL FCA 59-11-11, "Period and Damping Comparison of First and Second Powered X-15 Flights With the Flight Control Simulator"

6. NA-61-400, "X-15 Analog Flight Simulation Program - Systems Development and Pilot Training"

7. Hoey, Robert G., "Correlation of X-15 Simulation Experience With Flight Test Results," AGARD Report 530, May 1966

8. NA-65-398, "The Complete Six-Degree-of-Freedom XB-70A Hybrid Simulation"

9. ASD-TDR-63-711, "An Investigation to Determine Validity of Using a Simulator to Predict Landing Impact Characteristics, Volume I - Program Summary"

10. Stickle, J. W., "An Investigation of Landing-Contract Conditions for Two Large Turbojet Transports and a Turboprop Transport During Routine Daylight Operations," NASA TND-899, May 1961

11. IOL FDA-66-9-3, "HoTran Simulator and FS-001 Preliminary Data Correlation"

12. IOL FDS-66-9-13, "HoTran - FS-001 Flight Test Match"

13. Crane, H. L., "Preliminary Evaluation of Two Jet-Transport Simulators for the Investigation of Landing-Contact Conditions," NASA TND-1495, November 1962

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13. ABSTRACT

Many methods have been used to correlate ground-based simulators with the actual aircraft they simulate. Comparisons of simulation with flight in past NAA/LAD programs are presented. They include dynamic checks, performance checks, and comparisons at the statistical level.

Favorable comparisons not only validate the particular simulator involved but also give credence to the simulation process for future simulators. Good correlation between simulation and flight cannot be attributed to any one specific item. The overall handling and flying characteristics are embodied in the simulation process, but it is the attention to details which produces the distinguishing characteristics of a specific aircraft.

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